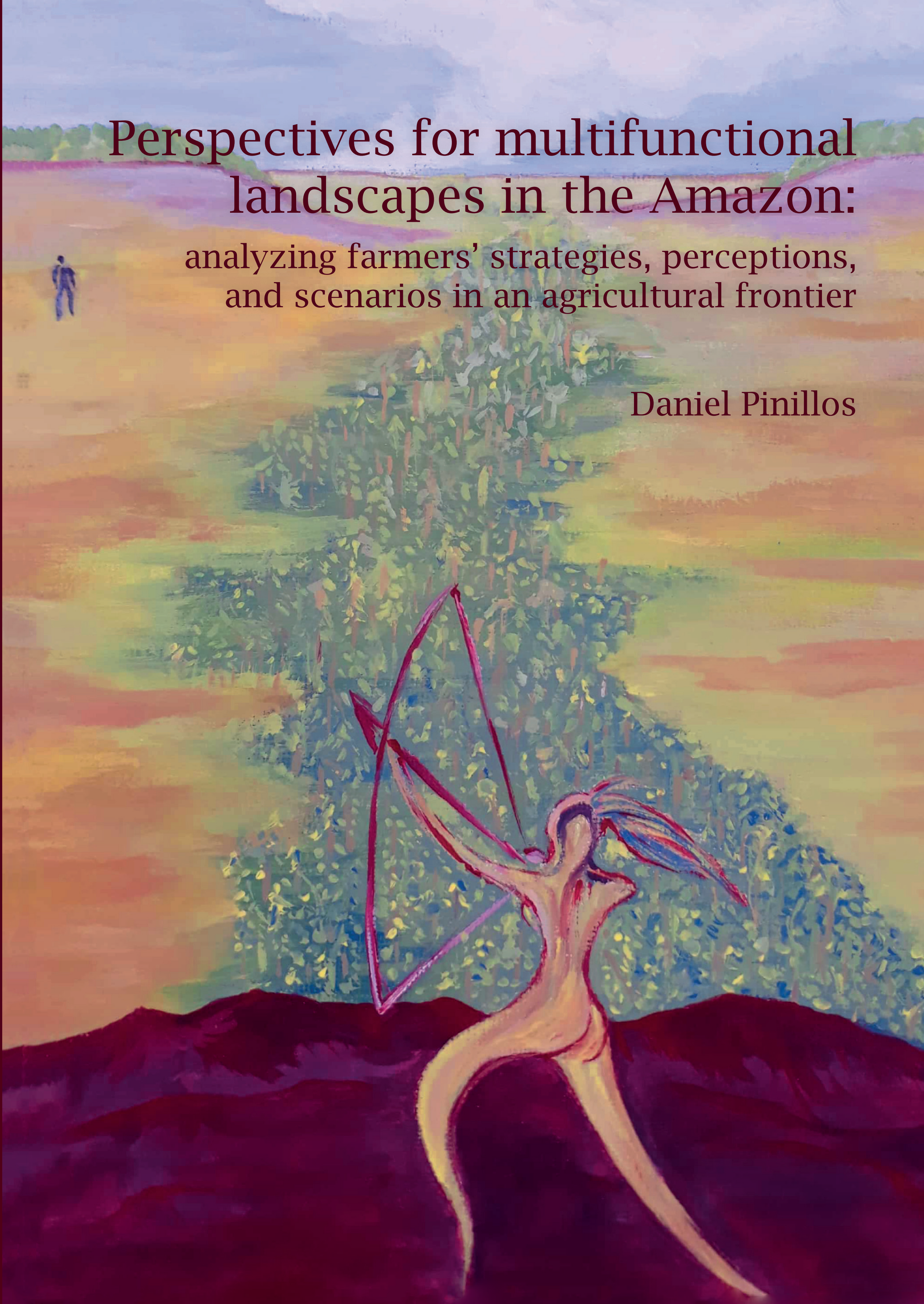

Perspectives for multifunctional landscapes in the Amazon:

analyzing farmers' strategies, perceptions, and scenarios in an agricultural frontier

Daniel Pinillos

Propositions

1. Scientific engagement with the agribusiness sector is fundamental to develop nature-based alternatives for agriculture in Paragominas. (*this thesis*)

2. Local recognition of forests as an integral part of rural development is a prerequisite for landscape multifunctionality in Paragominas. (*this thesis*)

3. The mind-body dichotomy undermines the efficacy of mainstream medicine.

4. The illusion of consciousness is an evolutionary strategy to manage entropy.

5. Scarcity of food and oxygen in living organisms can be physiologically regenerative.

6. Striving for quality of life is merely an attempt to recreate tribal human experiences of intimacy, playfulness and connectedness.

7. The "Let's feed the world" motto misleads attention from the structural global problem of disparity.

8. The confinement imposed by the Covid-19 pandemic is an opportunity for privileged individuals to explore what Jung calls "the shadow".

Propositions belonging to the thesis, entitled:

"Perspectives for multifunctional landscapes in the Amazon: analyzing farmers' strategies, perceptions, and scenarios in an agricultural frontier"

Daniel Pinillos

Wageningen, March 1, 2021

Perspectives for multifunctional landscapes in the Amazon: analyzing farmers’ strategies, perceptions, and scenarios in an agricultural frontier

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Perspectives for multifunctional landscapes in the Amazon: analyzing farmers' strategies, perceptions, and scenarios in an agricultural frontier

Daniel Pinillos

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Para Miriam y Carlos

Whereof one cannot speak, thereof one must be silent.

– Ludwig Wittgenstein

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Chapter 1

General introduction

1.1 The Frontier as a new world experience

Frontier theory derives from the work of U.S. historian Frederick Jackson Turner and his seminal essay 'The Significance of The Frontier in American History' presented at a congress of historians in Chicago in 1893. Turner argued that the western frontier of the North American continent has been the most significant factor determining the United States' character shaped by seemingly endless land availability, individualism, and a democratic drive (Hughes, 2002). According to Turner, the frontier was a line marking the furthest extent of civilization, but it was also a process of migration and settlement, while the evolution of North American civilization and identity took place (Turner, 1894; Hughes, 2002). Turner's theory has been widely criticized as a simplification of U.S. history of internal migration as well as a blatant ethnocentric interpretation of what otherwise was the eradication and displacement of native populations (Altenbernd and Trimble Young, 2014). Nonetheless, throughout the 20th century, Turner's notion of the frontier has contributed to forge the so-called "American belief in progress" where American exceptionalism and expansionist ideology rest (Billington, 1958; Lipset, 1996). The frontier imagery is a ubiquitous feature of U.S. society that till today is reflected in advertising, public policy, popular culture, and scientific and academic settings (Miller and Acs, 2017). Such imagery and vision of the frontier have also made its way in the Brazilian context as a reinterpretation of the Brazilian belief in rural modernization and progress (Vale, 2015).

Brazilians historians have described the history of Brazil in terms that resembles Turner's frontier, but more as a place than as a process (Lombardi, 1975). In his Capítulos de História Colonial ("Chapters of Colonial History"), Brazilian historian João Capistrano de Abreu talks about the "sertão" (backwoods) referring to the vast unexplored "Portuguese America" to denote a sense of frontier and wilderness (Lombardi, 1975). Capistrano de Abreu describes the sertão as an important factor shaping Brazilian identity when bandeirantes (literally "flag-carriers"), vaqueiros (cowboys from the Northeast region) and gaúchos (ranchers from the South region) conquered the continent from the Portuguese and the Brazilian coastal elites (Lombardi, 1975). Therefore, from the east coast to the continental interior, in both the North American and Brazilian context, the frontier represented a "fluidity of life" amidst the colonization of a continent (Lombardi, 1975).

The frontier represents an experience of space that morphs into ideologies that in turn shape the identity, narratives and imaginaries of people entering unknown places. Grabo (1987) calls "Frontier ideology" an oxymoron, as for him a frontier represents a blank canvas and the ideology behind it, the painting. Nevertheless, the frontier invites for external imposition of meaning where a diversity of interpretations and narratives can emerge and compete for dominance (Hughes, 2002). Enabling for multiple interpretations makes the frontier a plural entity that in the case of Brazil has shaped its history with violence and environmental destruction. Understanding the imagery, visions and aspirations of people living in frontiers from an historical perspective is key to understand the problems that this thesis tackles in light of historic environmental degradation and the ongoing pursuit of socio-economic development amidst a dynamic regional and global context. The *frontier* in its classical sense is a broad geographic zone characterized by abundant natural resources, low people to land ratio, and the mixing of people from different backgrounds progressively moving toward a mature economy and social order (Lombardi, 1975).

1.2 The Brazilian frontier and agricultural commodities

When the colonization of the Brazilian interior began in the 16th century, the Brazilian frontier started to divert into what Burns (1995) calls the “folk frontier” and the “official frontier”. The folk frontier was embodied by colonists escaping poverty and oppression first from the ruling colonial powers, and then from the State. The official frontier, on the other hand, represented the ruling authorities and its objective to expand North Atlantic capitalism into unknown territories of Brazil (Burns, 1995).

The confluence of these two frontiers have filled the history of the country with violent episodes such as the suppression of the community of escaped slaves in Palmares (current Alagoas State) during the 17th century, the war of Canudos in Bahia State in the late 19th century, or the Contestado war in southern Brazil between land settlers and landowners at the beginning of the 20th century (Burns, 1995). Amidst violence and wars, however, the frontier also contributed to shape the national identity. Burns (1995) talks about the “Brazilianization” of the population during these times as a process of miscegenation and cultural mix in the interior of the country far away from the coastal line and increasingly further away from European influence (Figure 1.1). The frontier was also a centripetal force that kept Portuguese America together in stark contrast to Spanish America that disintegrated into multiple smaller countries (Figure 1.2) (Burns, 1995).

Figure 1.1 Depictions of the "folk frontier" and the "official frontier" in late 19th and early 20th century paintings. On the left: "O Derrubador Brasileiro" (The Brazilian lumberjack) (1879) by José Ferraz de Almeida Júnior (1850-1899), the first Brazilian artist to portray the new ordinary people in its environment, challenging the prevailing theme of imperial glory in the plastic arts of 19th century Brazil. In this painting Ferraz de Almeida captures the protagonist of the folk frontier forging miscegenation and the emerging Brazilian identity (CHAA, 2017). On the right: "Conquista do Amazonas" (Conquest of the Amazons) (1907) by Antonio Parreiras (1860-1937), depicts Pedro Teixeira (the first European to travel up and down the Amazon River) and his expedition surrounded by the symbolic entrance of European civilization into the new world inhabited by indigenous populations. Although this painting dates back to the 20th century, it reinforces the idea of the Republic by exalting the conquest of the territory by the new State conveying a sense of power and dominance able to integrate all members of society (i.e., the official frontier) (de Castro, 2019).

Unlike the North American frontier and probably due to the restricting conditions imposed by vast and dense forests, the Brazilian frontier developed into multiple fragmented migration waves expanding from the northern, the northwestern, the southern and the São Paulo region into what some scholars have denominated "hollow frontiers" as they did not consolidated into permanent human settlement (Lombardi, 1975). Such intermittency of human settlements in these frontiers, can be linked to the economic models that were adopted based on the production of export commodities that were dependent on boom periods creating demographically empty frontiers controlled by relatively few wealthy landholders (Lombardi, 1975; Burns, 1995). The sugar industry, for example, was the central social institution of 17th century colonial Brazil that in the late 1650s would be overtaken by the Caribbean as the center of global sugar production (Moore, 2000). The collapse of the Amazonian rubber industry in the early 20th is another example of a commodity boom period leaving behind a hollow frontier (Barham and Coomes, 1996).

These developments led to the formation of "commodity frontiers" as spaces where supply chains operated by transnational organizations became the primary organizing mechanism to advance capitalist and entrepreneurial investments based on the exploitation of the environment in Brazil (Moore, 2000). Throughout the history of the country, this meant that the official frontier has prioritized the production of commodities for export over subsistence production, perpetuating class patterns, inequalities and land concentration (Burns, 1995).

1.3 The official frontier tames the Brazilian Amazon

Prior to the 20th century, the Brazilian Amazon was perceived as an impenetrable jungle of doomed infrastructure and development projects. An attempt to construct a railroad connecting the Mamore and Madeira rivers in Rondônia State in the 19th century was labeled the "Railway of the Devil" as it left tens of thousands of dead workers due to diseases, accidents, and wild animals (Hecht and Rajão, 2020). The collapse of the Amazonian rubber industry in the early 20th century reaffirmed the region as a place of failed ventures (Barham and Coomes, 1996).

These developments, nevertheless, prompted the Federal Government to adopt new strategies to advance the occupation of the Amazon in light of Dutch and British dominance on rubber trade in South Asian colonies, and the urge of the U.S. to secure latex supply for the automobile industry (Hecht and Rajão, 2020). From late 19th century until the 1950s, military governments deployed technocratic projects to develop land use models and maps that steered the effective occupation of the Amazon into the "Amazônia Legal" (the "Legal Amazon" covers about 5 million km² or roughly 60% of the country, encompasses the Amazon rainforest, the Pantanal, and portions of the Cerrado, it covers all seven states of the North region as well as most of Mato Grosso State and the western part of Maranhão State), the official and legally defined area for the entire Brazilian Amazon region (Hecht and Rajão, 2020). Progressively, this process aimed at transforming the Amazon from an impenetrable jungle into an agricultural commodity frontier capable of supplying the global industrial complex (Hecht, 2013). In the 1920s, a U.S.-led soil and vegetation survey mapped suitable areas for rubber plantations and the production of other commodities such as sugar, cotton, corn, rice, and the ranging of livestock (Hecht, 2013; Hecht and Rajão, 2020). In 1942, the Brazilian and the U.S. Governments signed a political-military agreement known as Acordos de Washington ("the Washington Accords"), in which Brazil agreed to supply rubber, iron, cotton, and other commodities crucial for the U.S. war efforts in exchange of weaponry, capital and technical cooperation (Hecht and Cockburn, 2010). This militarized commodity-oriented approach would provide a model for a centralized spatial planning rationale that, in combination with international capital and international NGOs, would conform the prevalent governance complex for the production of global commodities in the Amazon (Hecht and Rajão, 2020). Furthermore, in 1946 the creation of the Superintendência do Plano de Valorização Econômica da Amazônia (Superintendence for the Economic Recovery Plan of the Amazon) based on a development and modernization scheme advanced by the Tennessee Valley Authority in the U.S., furthered the technocratic approach and the U.S. participation in the consolidation of the Amazon as a global agricultural frontier (Hecht and Rajão, 2020).

Once Second World War was over, Brazilian politicians perceived the necessity to provide the population with an ideological conceptualization of the Amazon as a national asset through nationalistic slogans best embodied by the famous "integrar para não entregar" moto (integrate it or lose it) attributed to the military president Castelo Branco in the early 1960s; a slogan, nevertheless, that would endure throughout the entire military period (1964-1985) (Hecht and Rajão, 2020). The inauguration of the new capital Brasilia in 1960 was yet another milestone for the triumph of the official frontier advancing the national project of territorial integration of the Amazon, and later the construction of the Trans-Amazonian highway in 1972 literally paved the way for the effective colonization of the Amazon (Lombardi, 1975; Burns, 1995). This integration process gave rise to a myriad of frontiers across the country characterized by resource appropriation, abundant land, and natural resources, but scarce labor and capital. In these decades, cattle ranching became the main farming system in the Amazon: from a population of 80 million heads in the 1990s to 200 million nowadays making bovines the true colonizers of the Amazon basin (Veiga et al., 2002; Global Forest Atlas, 2019). Later, during the late 1990s, in the context of a globalized economy, regional integration and rapid technological development, corporate actors present in the region harnessed large landholdings devoted to export agricultural commodities supported by subsidies and deregulated access to land, creating so-called "neoliberal frontiers" (Hecht, 2005).

1.4 The frontier in Pará State

Since the 1970s the Amazon region has undergone massive land use changes and forest loss equivalent to roughly 15% of the total Amazon basin (Lemos and Silva, 2012). Currently, the frontier continues to be a dual process of land occupation. On one hand, the spontaneous migration of pioneers and peasants searching for land (i.e., the folk frontier of the past) and on the other hand, non-spontaneous agricultural expansion fronts driven by public policies and corporate ventures (i.e., the official frontier) (Martins, 1996). Violent encounters between these two frontiers still manifest as displacement of indigenous populations, land conflicts and land grabbing (Baletti, 2012).

Within this convoluted social context, a contemporary characterization of the Amazonian frontier is also framed in terms of land use and land cover, i.e., the deforestation frontier, where forest is cleared mainly for extensive cattle ranching (stretching from the southern to the eastern Amazon region, the so-called "Arc of Fire"), and the intensification frontier describing industrial soybean production and intensive cattle ranching expanding over large, cleared areas. These two land use frontiers also indicate the boundaries between low-capital, extensive agriculture, and intensive agriculture characterized by high investment capacity (Thaler et al., 2019).

In 2004, policies involving Federal, state, and municipal governments elicited a transition towards low deforestation and high productivity of the agro-industrial sector (Thaler et al., 2019). Deforestation rates in the Amazon declined by more than 70%, while soybean production doubled, and the cattle herd grew by 20% (IBGE 2018). Federal policies supporting these efforts included the Prevention and Control of Deforestation in the Legal Amazon plan in 2014, as well as governance measures stimulating agricultural intensification through the creation of new credit incentives stipulated in the Federal Low-Carbon Agricultural Plan (Plano ABC). At the same time, state-level initiatives, such as the state of Pará's green municipalities program, and initiatives of the private sector, such as a soybean moratorium in 2006 and a sectorial cattle agreement in 2009, contributed to the reduction of deforestation during the 2004-2012 period (Gibbs et al., 2015; Gibbs et al., 2016). The assignment of new conservation areas and indigenous territories was also an important factor in decreasing deforestation (Thaler et al., 2019).

Although these efforts made Brazil the largest global contributor to reducing greenhouse gas (GHG) emissions during the 2004-2012 period, over time the above actions have become less effective to contain deforestation, casting doubts on the long-term effectiveness of command-and-control measures (Schielein and Börner, 2018; Seymour and Harris, 2019). From 2014, deforestation rates in the Amazon and in particular in the state of Pará, have increased substantially (Fonseca et al., 2020). In light of this deforestation resurgence there are growing concerns that the Amazon region is reaching a tipping ecological point where the interaction between deforestation, climate change and forest fires could irreversibly turn the Amazon into degraded savannahs (Lovejoy and Nobre, 2018).

Pará State (1.2 million km^2) in northern Brazil constitutes a typical agricultural Amazonian frontier characterized by occupation led by governmental incentives that supported extensive livestock farms and colonization projects since the 1960s (Sauer, 2018). More recently in the early 2000s, the eastern and western parts of Pará have been occupied by soybean farms in response to government credits, and expansion of road infrastructure in conjunction with private investments (Sauer, 2018). This development has consolidated the agribusiness sector as a central feature of Pará's economy and constitutes part of a large agro-industrial complex that aims at increasing production and the competitiveness of the Brazilian agribusiness sector in the international commodity market (Kröger, 2017; Sauer, 2018).

1.4.1 Study site: the Paragominas municipality

Soybean monocultures in Pará State have increased from 26,000 ha in 1998 to over 433,000 ha in 2016 (IBGE 2017). The municipality of Paragominas (19,342 km^2) (Figures 1.2 and 1.3) in northeastern Pará, has become the hotspot of this soybean boom in the State with over 102,000 ha of soybean monocultures (Sauer, 2018). Paragominas has been shaped by frontier expansion dynamics associated with the construction of the Belém-Brasilia highway (BR-010), colonization policies and an economic model based on environment-degrading activities such as logging, slash and burn agriculture and extensive cattle ranching (Margulis, 2003).

In the early 2000s, when the Federal Government advanced its ambitious environmental policies to reduce deforestation in the Amazon, Paragominas was included in the blacklist of top deforesters which led to credit restrictions and the Operação Arco de Fogo (Arc of Fire Operation), a government campaign to deter illegal deforestation with a hardened militaristic approach. In 2008, this brought together the Municipal Government and rural elites to launch the Green Municipality initiative as a social pact to end large-scale deforestation in Paragominas and register all rural properties in the Environmental Rural Registry (CAR) to monitor deforestation inside private landholdings. These actions made Paragominas the first municipality in 2010 to exit the infamous list and the Municipality became a model that then the State Government replicated across Pará.

The Green Municipality initiative elicited a process of land use intensification and diversification into mechanized agriculture and timber plantations in open available areas (Tritsch et al., 2016). The process, nevertheless, was limited in its scope to foster landscape management towards more resilient, sustainable landscapes (Piketty et al., 2015). For example, forest degradation from selective logging and fires persists in Paragominas to this day causing carbon and biodiversity losses (Berenguer et al., 2014; Barlow et al., 2016). The Green

Municipality program also lacked notions of spatial land use organization to manage and restore vast areas of degraded soils (Piketty et al., 2015). On the social dimension, it did little to prevent further marginalization of family farmers (Viana et al., 2016).

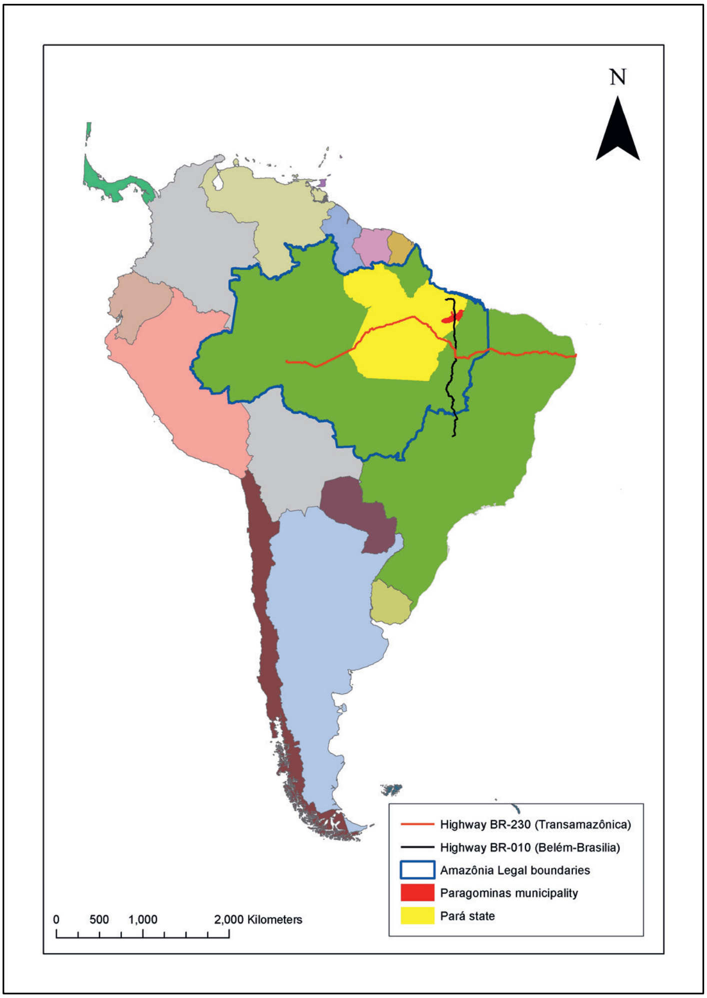

Figure 1.2 Geographical location of the Paragominas municipality in northeastern Pará State, Brazil. Brazil's continental size of 8.5 million km² makes it the 5th largest country in the world with a population of 211 million. Pará State (1.2 million km²) is the second largest Brazilian state similar in size to Angola (23rd largest country in the world) or approximately two times the size of France, and a population of only 8.6 million people (7 inhabitants/km²). The Paragominas municipality, founded in 1965, stretches across 19,342 km² (approximately half the size of the Netherlands) with an estimated population of 114,503 inhabitants (6 inhabitants/km²). The colonization of Paragominas was prompted by the construction of the BR-010 highway (1,950 km) laid down in the early 1960s, while the Trans-Amazonian highway was introduced in 1972 and spans over 4,200 km (The Economist, 2014; IBGE, 2020; The World Bank, 2020).

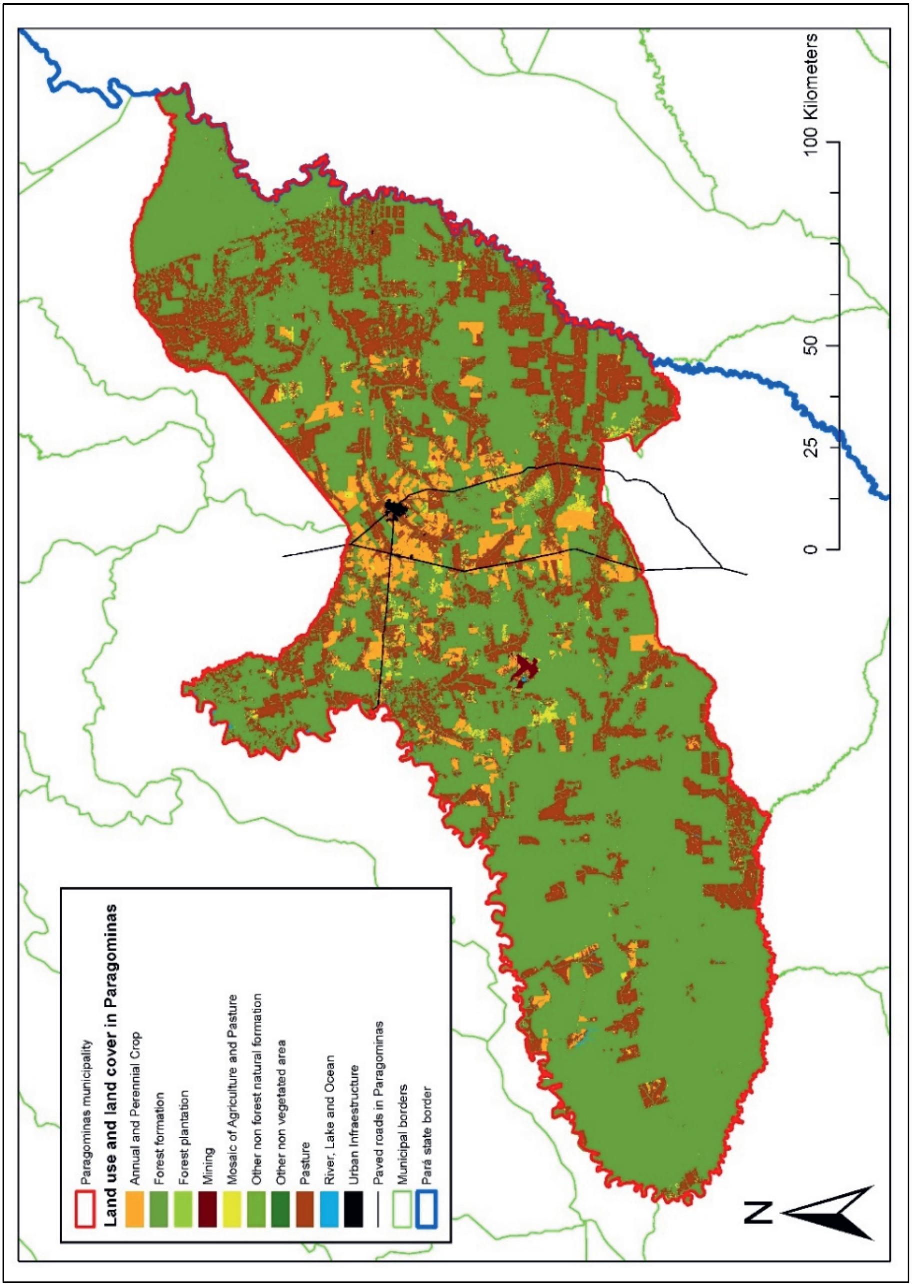

Figure 1.3 2017 Land use and land cover of the Paragominas Municipality. Source: MAPBIOMAS (2020).

1.4.2 Problem statement

While for the short term, large-scale deforestation in Paragominas is under control (below 25 km^2) suggesting a post-forest frontier context, we are unsure of the longevity of this status quo, particularly, given a history of frequent policy and market changes in the region. How can we sustain and further enhance synergies between forest protection and the provision of livelihoods? Specifically, what types of land use spatial arrangements can reconcile forest conservation and agricultural production in the long term in Paragominas? Furthermore, it is not clear what farming systems emerge as a result of reduced access to land as a consequence of forest conservation. There is also limited understanding on what the main social actors, i.e., farmers and landholders, make of the policy changes that first convoked to deforest and colonize the region, and then punished deforestation.

Paragominas, therefore, is at a crossroad between a path of landscape consolidation towards a post-forest frontier context, and a path where the agricultural frontier will eventually push forward in detriment of the forest emulating the historical trajectory. Thus, there is an urgent need for developing information for land use planning and governance initiatives that promote structural pathways aimed at rural development and forest conservation that better account for societal demands in a sustainable way.

1.4.3 Ecosystem services in the Paragominas frontier

To develop information that underpins reconciling agricultural intensification and forest conservation in Paragominas, I apply the concept of Ecosystem Services (ES) which can be understood as the benefits that humans get from ecosystems classified into four categories: provisioning (e.g., water and food), regulating (e.g., climate, flood and pest control), supporting (e.g., nutrient cycling, soil formation) and cultural (e.g., aesthetic, recreational and spiritual values) (Millennium Ecosystem Assessment, 2005; Haines-Young and Potschin, 2010). Therefore, ES are social constructs that exist where humans gain some degree of wellbeing from their interaction with ecosystems (Balvanera et al., 2015).

The Amazon basin is one of the world's most important providers of ES as it encompasses the largest area of tropical rainforest and biological diversity in the world (Foley et al., 2007). The Amazon provides ES such as timber and food, but also ES of regional and global environmental importance such as pollination, flood control, carbon storage, climate and water cycle regulation, and control of vector borne and water borne diseases (Foley et al., 2007). In this thesis, I focus on 1) agricultural commodity production (provisioning ES), 2) carbon storage (regulating ES), and 3) habitat for biodiversity (supporting/regulating ES).

The Amazon accounts for 10% of the world's terrestrial productivity for biomass and soil organic carbon storage by removing it from the atmosphere (Melillo et al., 1996; Malhi and Grace, 2000; Malhi et al., 2014). Land use change, forest degradation and fragmentation constitute important factors of direct carbon emissions into the atmosphere (Nepstad et al., 1999; Fearnside et al., 2009; Berenguer et al., 2014). Since the 1970's, it is estimated that the Amazon biome has lost 11.2 Pg C (1 Pg = 10^{15} g = 1 Gigaton) due to land use change and forest degradation (Nogueira et al., 2014).

Biodiversity on the other hand, encompasses the number, abundance, functional variety, spatial distribution and interactions of genotypes, species, populations, communities, and ecosystems (Loreau, 2010). Biodiversity holds a complex, multilayered relationship with ES as it has a key role regulating ecological processes linked to several ES (Mace et al., 2012). For example, increasing horizontal diversity (i.e., number of species within trophic levels) may, in theory increase ecosystem functions enhancing ES, while increasing vertical diversity (i.e., number of trophic levels), does not necessarily has the same positive effects towards ES (Loreau, 2010).

Provisioning and regulating ES are influenced by biodiversity due to "complementary effects" between species that combined with spatial heterogeneity can lead to higher rates of ES provision than the sum provided by its component species separately (Balvanera et al., 2015). Furthermore, the so-called insurance hypothesis suggests that asynchronous responses of species to environmental fluctuations can also lead to greater and more stable provision of ES in biodiverse habitats as compared to less biodiverse habitats (Balvanera et al., 2015). Furthermore, structurally complex agroecosystems may be able to compensate for high intensity management due to the effect of connected habitats supporting high biodiversity and concomitant capacity to absorb disturbance, i.e., resilience. In simplified landscapes the local allocation of habitats becomes crucial since the absence of a set of species necessary to harness the potential of ecosystem functions endangers the stability of ecological local processes (Tscharntke et al., 2005). Biodiversity is therefore threatened by the loss of natural habitats and climate change, but the potential to simultaneously protect carbon rich habitats and biodiversity in tropical landscapes depends on the relationship between biomass and tree diversity (Sullivan et al 2017). For instance, higher tree diversity may promote higher carbon stocks per unit area in tropical forests, but it is uncertain if these positive effects take place at regional or continental scales. Therefore, in the absence of a clear stand-level biodiversity-carbon relationship, carbon storage and habitat for biodiversity ought to be considered as separate objectives (Sullivan et al., 2017).

Moreover, ES interact as bundles that manifest together across space or time in a positive (synergy) or negative (trade-off) association (Spake et al., 2017). Deforestation in the Amazon implies an inherent trade-off between ecosystem goods readily available and yielding economic benefits in detriment of ES associated with long-term ecosystem functioning (e.g., non-timber forest products, pollinating insects, climate regulation, carbon storage, water regulation and purification, regulation of atmospheric circulation, control of infectious disease) (DeFries et al., 2004; Foley et al., 2007). Therefore, the supply of ES is not only determined by biodiversity and biophysical variables underpinning ecological functioning, but also by the interactions between ecosystems and societies through coupled social and ecological systems (Balvanera et al., 2015). The assessment of trade-offs between ES requires informed decisions to balance short-term social and economic benefits and long-term ecological functioning (De Fries et al 2004).

In this thesis I apply a landscape approach to assess both ecological and societal aspects of the supply and demand of ES to elucidate pathways that structurally reconcile agricultural production and forest conservation in the municipality of Paragominas.

1.5 A landscape methodological approach in Paragominas and thesis objectives

A landscape approach is a methodological concept encompassing several disciplines to study and explore human environmental challenges in an integrated manner (Arts et al., 2017). It enables tools and concepts for exploring and assessing potential competing social, economic, and environmental objectives (McCall, 2016). A landscape approach allows focusing on socio-ecological systems composed by different land uses and intersectoral actors, while at the same time the landscape boundaries can be fuzzy as scales depend on the specific objectives and processes that are examined (McCall, 2016).

A landscape approach allows for the assessment of geomorphological aspects of the land, such as soil and topography, biophysical aspects such as habitat and land cover, human activities, and land uses, as well as its interplay with stakeholder perceptions to shed light on more nuanced subjects such as ideologies, sense of identity and values. In Paragominas, a landscape approach is also advantageous to analyze the scales and functions associated to environmental vulnerabilities as these are not evenly distributed across the region, and to recognize the need for adaptive management and stakeholder involvement (Sayer et al., 2013). The landscape, therefore, manifests as an emergent property from the interaction of biophysical factors, land uses, land management practices and ecological processes (Poccard-Chapuis et al., 2014) where socio-economic, institutional and environmental dimensions interact across scales composing a socio-ecological system (Young et al., 2006).

A major challenge towards deriving pathways and transitions in a frontier landscape is the biophysical heterogeneity at different temporal and spatial scales, as well as heterogeneity of actors and societal demands. Frontier agroecosystems typically favor bifunctional landscapes, with a physical separation between areas of intensive agricultural production and biodiversity conservation (so called land sparing strategy), where relatively few people are involved, and benefits usually flow to a small set of large landholders. Multifunctional landscapes on the other hand, are prone to be diverse in its physical composition and in the set of ES accessible to a broader range of stakeholders within a local context (Fischer et al., 2017).

Landscape management requires long-term involvement of stakeholders to elicit collaboration among different groups of land managers, landholders, and institutions to meet multiple objectives required from the landscape (e.g., agricultural production, biodiversity conservation, cultural and spiritual services, environmental protection). A critical point of these collaborative processes to minimize trade-offs between ES and strengthen synergies between landscape objectives, is enabling processes of social learning that generate innovations addressing multiple societal demands (Scherr et al., 2014).

In this thesis, I focus on medium and large rural landholdings[1], which cover 95% of the area in Paragominas (the other 5 % is composed by settlements and Indigenous Reserve Alto Rio Guamá) and are in the hand of landholders who migrated to the region at several points in time since the inauguration of Paragominas[2] in 1965. These are key actors to address large-scale deforestation in the Brazilian Amazon because medium and large landholders are the ultimate decision-makers concerning land use and managerial decisions that can reconcile forest conservation and agricultural intensification in Paragominas. Moreover, the underlying factors of deforestation for the expansion of commercial agriculture are driven by global market demands that are not prone to disappear or reduce in the foreseeable future. Thus, addressing

[1] The National Institute for Colonization and Agrarian Reform (INCRA) classifies rural properties in terms of size as small, 1-4 *módulos fiscais* (MF); medium, 4-15 MF; large, more than 15 MF. A MF is a land measure unit adapted to the local characteristics of each municipality in terms of agricultural orientation and rent. In Paragominas a MF is equivalent to 55 ha (https://www.embrapa.br/en/codigo-florestal/area-de-reserva-legal-arl/modulo-fiscal).

[2] The name "Paragominas" is an abbreviation of the names of three states: Pará, Goiás (origin of the first pioneers that arrived to the region), and Minas Gerais (origin of the first investors predominantly miners) (https://paragominas.pa.gov.br/o-municipio/historia/).

this challenge requires a multidisciplinary approach to understand how the socio-ecological system of Paragominas is influenced by external drivers from social, economic, and political domains.

1.5.1 Thesis objectives

The objective of this thesis was to identify trade-offs between ES, opportunities, and pathways to enhance landscape multifunctionality in terms of carbon storage, habitat for biodiversity and agricultural production through land use planning and land management in the municipality of Paragominas, in the eastern Amazon region (Figure 1.4). The specific objectives are:

1. To characterize and describe the landscape in terms of trade-offs between carbon storage, habitat for biodiversity and agricultural commodity production (Chapter 2).
2. To understand farm diversity and its implications for agricultural intensification and diversification (Chapter 3).
3. To understand landholders' perceptions regarding forest conservation in private lands and its link with agricultural intensification (Chapter 4).
4. To explore the effects of landscape structure and land use change on carbon storage under contrasting land use and land cover scenarios (Chapter 5).

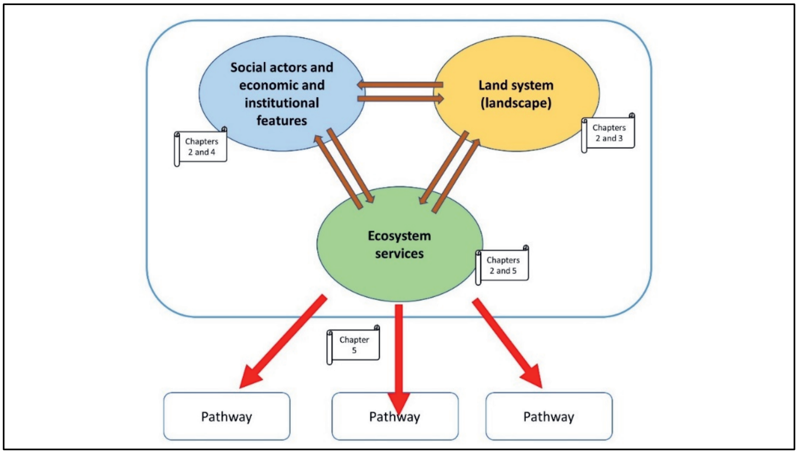

Figure 1.4 Research focus of this thesis, the frontier socioecological system in Paragominas conformed by 1) social actors, economic and institutional factors, 2) the biophysical system, and 3) ecosystem services, to envision pathways towards landscape multifunctionality.

Chapter 1

1.5.2 Thesis outline

In this thesis I apply multiple methods to find patterns and usable information for managing the prevailing heterogeneity of the landscape across multiple scales (i.e., the Municipality, rural landholdings, and perceptions), but also across exogenous domains that influence the local socio-ecological system (e.g., State, and Federal Government, the Amazon region, globalized markets, etc.). My research questions are addressed in each one of the chapters, respectively. I conceive the socio-ecological system of Paragominas as both a forest and agricultural frontier, and methodologically, the progression of the thesis can be understood as studies across spatial scales. Starting from the entire municipal region, in which the analysis is based on spatially explicit analysis using GIS tools (Chapter 2), zooming in on the landholding scale through farm surveys (Chapter 3), then into landholder perceptions based on semi-structured interviews and Q methodology (Chapter 4), back to the municipal scale where I generate anticipatory scenarios of land use and land cover (Chapter 5). Across the chapters, factors pertaining to higher scales such as state and federal policies, regional and global markets, are embedded in my analyses to be able to contextualize my results.

In Chapter 2 (Specific objective 1), I focus on the landscape and ES. I apply the conceptual framework of Functional Land Management (Schulte et al., 2014; Schulte et al., 2015) to conduct a spatial diagnosis of the landscape (Figure 1.5) at the municipal level in terms of the provision of carbon storage, habitat for biodiversity and commodity production. In Chapter 3 (Specific objective 2), I focus on rural landholdings and develop an inductive typology of farming systems in Paragominas (Figure 1.6) based on quantitative data that I collected via farm surveys and analyze using principal component analysis and cluster analysis. In Chapter 4 (Specific objective 3), I focus on the actors and apply Q methodology, a method developed in the field of psychology to account for human subjectivity (Figure 1.7), to understand landholder perceptions on the main forest conservation policy instrument in Brazil requiring landholdings in the Amazon to keep between 50-80% of the area as forest (i.e., Legal Reserves). In Chapter 5 (Specific objective 4), I generate anticipatory scenarios (Figure 1.8) based on a land use and land cover reclassification following different land use allocation strategies (land sparing, land sharing) and management priorities (i.e., forest conservation and agricultural production). Using the InVEST model (Sharp, 2020), I estimate carbon storage for these scenarios under a 15-year period in accordance with national and state environmental policies. In Chapter 6 (General discussion), I integrate my results and discuss these in the context of environmental governance developments currently taking place in Paragominas (i.e., a municipal development plan based on a territorial intelligence framework and landscape certification) to indicate how the insights generated in my thesis could be used within this process towards landscape multifunctionality. I then critically analyze processes of environmental governance in the Amazonian context to emphasize on the importance of considering the frontier of Paragominas as a socio-ecological system within a regional and global context influencing its trajectory. Finally, I take on the concept of land system science to draw theoretical links with landscape ecology to point out the importance of inter and transdisciplinary research and knowledge to envision pathways towards landscape multifunctionality.

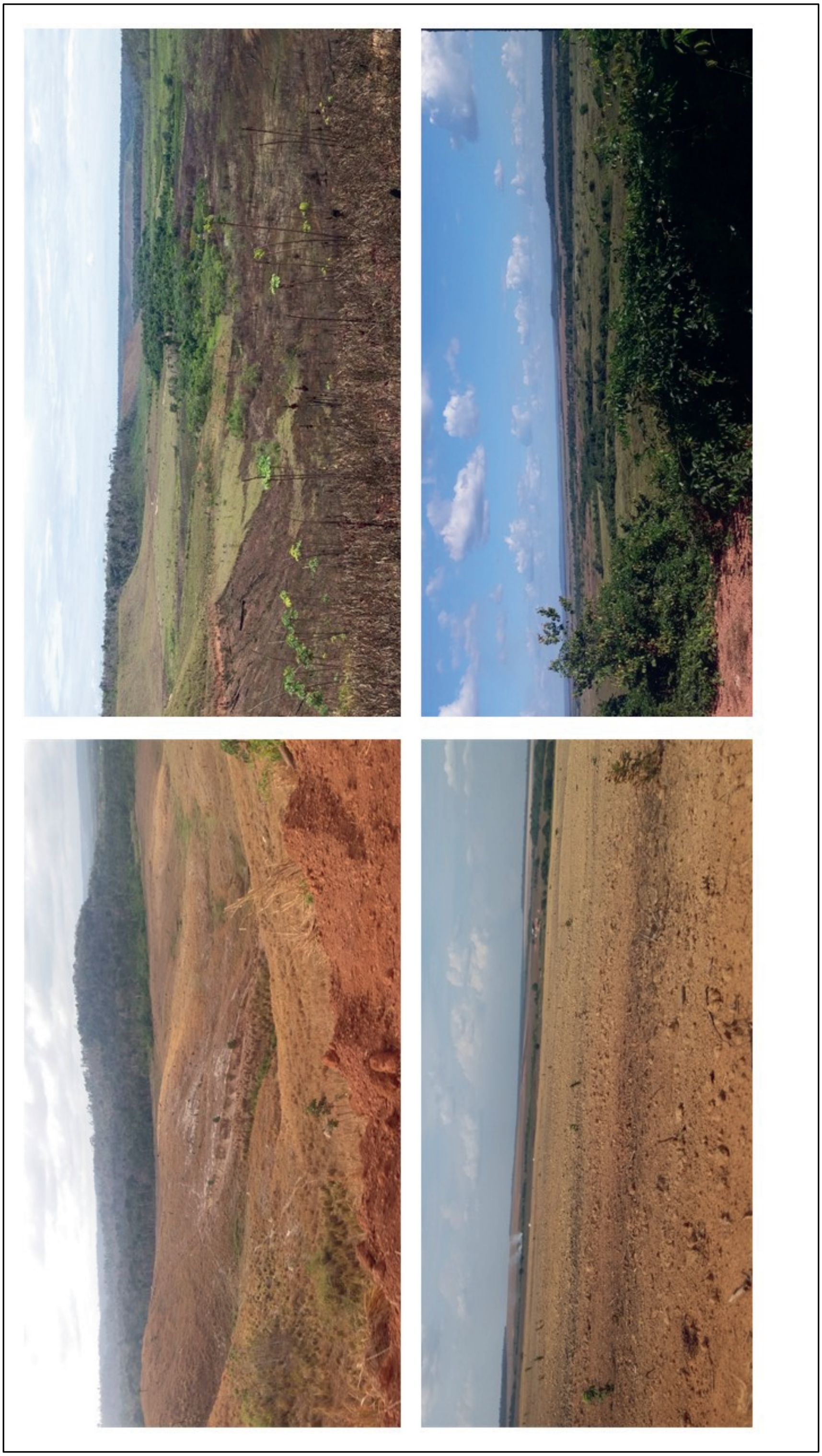

Figure 1.5 Panoramic views of the Paragominas landscape characterized by soil erosion, degraded forest, and natural regeneration of secondary forest.

Figure 1.6 Diversity of farming systems in Paragominas: a silvo-pastoral system (left), soybean monocultures (middle), and pastures (right).

Figure 1.7 Q methodology application to capture landholders' perceptions on Legal Reserves in Paragominas.

Figure 1.8 A 300 ha Cacao-teak-mahogany agroforestry system in Paragominas as a reference to envision anticipatory landscape scenarios.

1.6 Acknowledgements

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Chapter 2

Understanding landscape multifunctionality in a post-forest frontier: supply and demand of ecosystem services in the eastern Amazon region

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Abstract

Sustainable food production requires approaches that reconcile agricultural production with the conservation and sustainable use of natural resources, biodiversity, and associated ecosystem services. While the contribution of agriculture to the provision of individual ecosystem services has received considerable scientific attention, little is known about the extent to which tropical landscapes can meet societal expectations related to food production and environmental sustainability simultaneously. We assessed how the spatial configuration of pedo-morphology and land uses influences the provision of three soil-based ecosystem services in the eastern Amazon region: carbon storage (CS), habitat for biodiversity (HB) and agricultural commodity production (CP). We use the Functional Land Management framework to assess the supply and demand of these ecosystem services in a spatially explicit manner to identify areas of (mis)matches and trade-offs in the municipality of Paragominas, Brazil. The supply of ecosystem services was informed by a literature review for the various combinations of pedo-morphological characteristics and land uses in the region. The demand for ecosystem services was mapped based on federal and state policy targets. Mapping the supply and demand of CS indicated that half of the carbon in the region is stored in remnants of undisturbed forest which cover only a third of the municipality. Demand for HB in terms of forested area is met but it does not guarantee safeguarding biodiversity. Roughly a third of the territory shows scarce quality of HB even when compliant with legislation. Concerning CP, we identified areas where both supply and the demand to increase production are relatively high due to road access and lower intensification costs. The demand for agricultural production can eventually incentivize the expansion of agriculture on fertile soils, which could compromise environmental targets. Our results suggest that the simultaneous delivery of multiple ecosystem services may require land use pathways that combine land sparing and sharing approaches. Our analysis can inform integrated land use planning initiatives where, historically, the supply and demand for CP have been the single dominant driver for the current landscape configuration.

Key words: Landscape multifunctionality, ecosystem services, pedo-morphology, land use, policy targets, land use pathways

2.1 Introduction

With the growing human population in many parts of the world there is a challenge to reconcile food production with the conservation of biodiversity and associated ecosystem services. This requires that the production of higher volumes of food is accompanied by profound changes in the way food is produced, accessed and distributed (Holt-Giménez et al., 2012). The Amazon basin is a crucial region to tackle this challenge due to its unrivalled biodiversity, its regional and global regulating function of the carbon and hydrological cycle (Barthem et al., 2004; UNEP, 2009; Townsend et al., 2011), and its massive potentially available area for cropland expansion (Eitelberg et al., 2015). More than half of the Amazon rain forest is in Brazil, and of this portion, one fifth of the forestland has been cleared since the 1970s (WWF, 2019). The major cause of this loss is land use changes driven by the development of subsistence agriculture, large-scale monocultures, and livestock production (Barthem et al., 2004).

Between 2004 and 2012, public and private forest conservation measures triggered a sharp decline of deforestation rates in the Brazilian Amazon (Nepstad et al., 2014). Nevertheless, these have resurged since then, casting doubts on the long-term effectiveness of command-and-control measures to protect biodiversity (Fearnside, 2017a; Schielein and Börner, 2018). In forest frontiers of the eastern Amazon region, land use change from primary forest to agricultural land takes different forms depending on road accessibility, population density, governance and cultural background of settlers (Schielein and Börner, 2018). Therefore, in addition to restrictions on deforestation, agricultural intensification and diversification is recognized as a critical step to conciliate biodiversity conservation and agricultural production (Macedo et al., 2012; Barretto et al., 2013). Considering this, it is not clear which spatial land use configurations can reconcile ecosystem services at the landscape scale. Since land use change often threatens natural resources and the continued delivery of ecosystem services, there is an urgent need for developing land use planning that better accounts for the societal demands for ecosystem services, and the biotic and abiotic characteristics of the land to support these ecosystem services (Tittonell, 2014; Schulte et al., 2015).

We explore transition pathways in the municipality of Paragominas in northern state of Pará by taking a spatial approach and asking what spatial arrangements of land uses can enhance the provision of ecosystem services given a recent past of deforestation. Our study focuses on the landscape scale to draw an integrated assessment of the land in terms of the delivery of ecosystem services and societal demands thereof. We focus on three soil-related ecosystem services, carbon storage (CS), habitat for biodiversity (HB) and commodity production (CP) due to the tension between nature conservation and agricultural production (i.e., trade-offs between ecosystem services) that originated since the inception of the current landscape six decades ago (Schmink and Wood, 1992).

The objective of this study is to identify priority areas and targeting of interventions aimed at augmenting specific functions of land management, including carbon storage, the enhancement of biodiversity and the provision of agricultural commodities. We analyze the landscape at the lower jurisdictional level (i.e., municipality), to integrate multiscale demands and local governance to manage potential trade-offs between conservation and development. Jurisdictional approach is a term recently coined to indicate a landscape governance that seeks common goals among government, community stakeholders and businesses (Pacheco et al., 2017). In the Amazonian context, this approach refers specifically to greening commodity chains and complying with zero-deforestation policies. By identifying areas where land use changes would be most effective to meet societal demands while preserving the region's natural capital, our analysis can contribute to develop context-specific transition pathways to enhance landscape multifunctionality and resource-use efficiency in the eastern Amazon region.

2.2 Methods

2.2.1 Study site

Our study was conducted in the municipality of Paragominas in the northeastern state of Pará, Brazil. The municipality is located at one of the oldest agricultural frontiers in the Brazilian Amazon currently transitioning towards land use intensification as an array of policy measures have prompted the end of extensive deforestation. Such measures include the revision of the Forest Code in 2012 with a strong focus on protecting natural vegetation both in public and private lands, restricting credits to illegal deforesters, blacklisting municipalities deforesting illegally, implementing supply chains moratoria and command-and-control mechanisms (Piketty et al., 2015; Azevedo et al., 2017; Nunes et al., 2019).

Paragominas, nevertheless, has a history of intensive forest logging and livestock grazing that ignored key biophysical and environmental aspects for the spatial planning of these activities, such as land relief and soil characteristics (Poccard-Chapuis et al., 2014). This trajectory has shaped the landscape of the region (Rodrigues et al., 2014) into a disconnected mosaic of regrowth and degraded forest, old fields and low-productivity pastures (Nepstad et al., 1991; IBGE, 2016). In turn, these land use dynamics have led to soil degradation, disruption of nutrients cycling, biodiversity loss and increased fire susceptibility (Uhl and Kauffman, 1990; Nepstad et al., 1999; Barlow et al., 2016).

Pedo-morphological conditions in the region follow a specific pattern of monoclinal sedimentary units with a lateritic pedo-genesis that results in geomorphological surfaces of different soil textures and erosion conditions (Laurent et al., 2017). In Paragominas this manifests as plateaus of 160-190 m.a.s.l., separated by valleys of up to 10-12 kilometers wide (Laurent et al., 2017). As a result of the genesis of the bedrock and the local topography, plateaus in the Paragominas region are covered by the so-called Belterra clay (clayey Ferralsols with70-80% kaolinite), upper valley slopes are covered by gravel soils, while the bottom of the valleys are covered by loamy sand Ferralsols (Rodrigues et al., 2003; Laurent et al., 2017). Soil texture, in turn, is one of the main determinants of soil fertility, erosion, compaction, cation exchange and water holding capacity (Laurent et al., 2017). Therefore, our study site was first classified into pedo-morphological units that represent combinations of soil texture, slope, and proximity to water bodies (Figure 2.1). We limited our analysis to clayey plateaus and sandy valleys, which account for 77% of the territory in Paragominas. We assumed a consistent soil type-pedo-morphology relationship across the study area (Laurent et al., 2017). Regarding land use, we classified the region into managed areas (mechanized agriculture, pastures, and forest plantations), unmanaged areas (natural regeneration and degraded forest) and conservation areas (undisturbed forests).

2.2.2 Research approach

We define a landscape as the spatial organization of biophysical characteristics and land uses driven by ecological processes and management practices (Poccard-Chapuis et al., 2014). Land use decisions, however, are mostly made at the farm scale and public policies are regulating these decisions. In this conception, socio-economic, institutional and environmental dimensions interact across farm, landscape and municipal scales composing a socio-ecological system (Gallopín et al., 2001). We use the conceptual framework of Functional Land Management (FLM) (Schulte et al., 2014; Schulte et al., 2015) to spatially identify areas where land is being used and managed in such a way that ecosystem services provision is not optimal and can be enhanced. By recognizing soil multifunctionality, FLM aims at the optimization - rather than maximization - of soil-based ecosystem services, given the difficulty of maximizing all functions at the same time across scales. We refer to ‘supply’ as the provision of soil-based ecosystem services as a function of biophysical characteristics, land use and management, whereas ‘demand’ is derived from agro-environmental policies acting as proxies of societal expectations (Schulte et al., 2015).

We considered pedo-morphology and land use as the two main drivers of the supply of ecosystem services in Paragominas. Thus, to manage the complexity of the socio-ecological system at the municipal level (19,342 km^2), we first categorized the region into landscape units (LU) defined as the combination of pedo-morphological conditions (Figure 2.1) and land use categories (Schulte et al., 2014; Coyle et al., 2016). To assess the ecosystem services supply for each LU, we reviewed the literature on the link between the provision of ecosystem services, pedo-morphological conditions, and land use. We assumed that these two bio-physical conditions (i.e., pedo-morphology and land use) will be the prime drivers of ecosystem services supply at the landscape scale because of their link with soil texture and land cover, respectively. First, we focused on the relation between each one of the ecosystem services and soil textural class as it conditions soil carbon storage capacity, soil fertility and the likelihood that habitats for conservation will be competing with agricultural production in the region. We selected only studies from the Amazon and Cerrado biome except for the soil texture-soil biodiversity link as we did not find a relevant study for Brazil. This first literature review allowed us to qualitatively assess the (spatial) heterogeneity of the supply in relation to soil texture to build an informed categorization of LUs and capture general trends at the municipality level in relation to pedo-morphology.

A second literature review was conducted to assess the local delivery of CS and HB at land use level using studies conducted in Paragominas. Carbon storage for major land use/land cover types was assessed using the Invest Carbon Model (Sharp et al., 2014). We estimated carbon stocks by summing secondary data on soil carbon and aboveground biomass. Data on carbon in belowground biomass, dead and harvested wood were not available and were therefore not included in the analysis. For the supply of HB, we derived an index based on recorded number of species for birds, dung beetles, orchid plant bees and ants for each land use type (i.e., α-biodiversity at the site level) reported in the literature. To calculate indices, we took the highest value for each indicator specified in Table 2.1 and assigned this a value of 1. The remaining values were divided by the maximum value to generate a relative scale with a maximum value of 1. Concerning CP, we selected the three main commodities produced in the region: soybean, beef, and wood products, and assessed their gross profit margin and investment return period as indicators of commodity supply. We chose economic indicators because these capture one of the three main dimensions to assess productive performance of land use systems (besides the ecological and agronomic dimension; Murray et al., 2016), and can be quantified for crop, beef, and forest production. We estimated the gross profit margin for each commodity based on official exports statistics for the year 2017, and other sources from scientific and grey literature reporting on internal markets, production costs and profit margins in Brazil from 2004 to 2018 (Table 2.1).

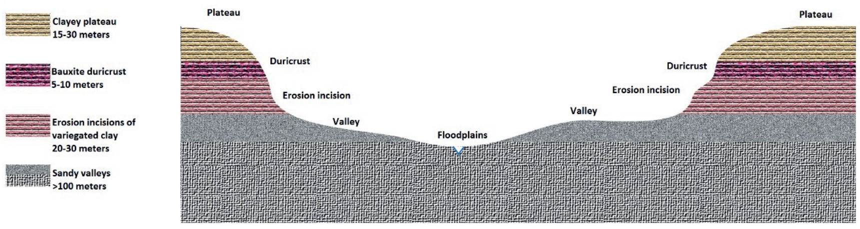

Figure 2.1 Geological profile and pedo-morphological units in Paragominas northeastern Pará State, Brazil.

To frame the societal demands for ecosystem services delivery, we conducted reviews of the relevant policy frameworks related to CS, HB, and CP in Brazil. These included national policies, state legislation and municipal regulations. We selected policies that explicitly state specific targets for our three ecosystem services. The selection of the demand indicators was based on these targets. In the case of CS, the targets include reducing national carbon emissions by 37% in 2025 in relation to 2005, and a ban on deforestation at the municipal level. The demand for HB was taken as the mandate to preserve 50 to 80% of each rural property as a forest conservation area, whereas the demand for CP was derived from the state-level targets aiming at annual production increases until 2030. We also considered road infrastructure as underlying drivers of agricultural intensification.

Once indicators and values were developed and estimated both for supply and demand, we generated maps for the supply of ecosystem services by intersecting a map of pedo-morphological units (which encompasses the corresponding soil textural categories) with a map of land use of Paragominas in Esri ARCGIS 10.4. This generated a map of LUs that then were attributed the indices derived from the literature (Figure 2.2) and illustrated in our supply matrix (Figure 2.3). Regarding the demand maps, the spatial variation was not defined based on the LU classification, but rather on the targets established in the policies and their application at the municipal level.

Finally, to explore land use pathways to enhance landscape multifunctionality, we integrated the supply and demand maps for CS, HB, and CP (Figure 2.5) to generate a trade-off map for these ecosystem services (Figure 2.6). We first standardized the supply and demand maps for CS, HB, and CP by generating maps with z-scores at the pixel level (630 x 630 m = 40 ha). Then the z-score transformed demand and supply maps were subtracted for each ecosystem service to reveal areas where supply meets or fails demand. The spatial distribution of trade-offs between CS, HB and CP were then integrated in a single map by systematically considering all eight (2^3) combinations of potential (mis)matches between CS, HB, and CP (Figure 2.4). All calculations were conducted in ArcGIS 10 using the raster calculator.

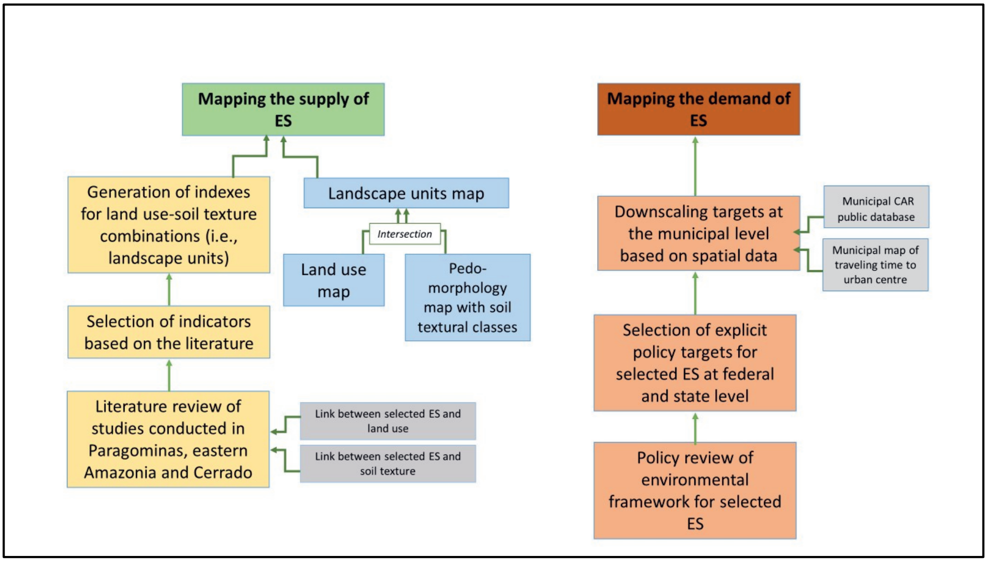

Figure 2.2 Diagram of methodological steps followed to map the supply and demand of ecosystem services in Paragominas.

2.2.3 Supply of soil-based ecosystem services

Clay content is an important factor driving carbon dynamics and storage in tropical soils whereby clay content is usually positively associated with soil carbon storage capacity (Feller and Beare, 1997; Six et al., 2002; Telles et al., 2003). For example, in a study conducted on arable and native vegetation land in the Cerrado biome, Neto et al. (2010) reported a significant linear increase of soil organic carbon (0-20 cm) with clay content. In a study conducted in the eastern Amazon region, Silver et al (2000) reported significantly greater soil carbon content in clayey soils than in sandy soils at 20 cm. Another study conducted in clayey and sandy soils of the same forest in the Amazonia state, reported that at 40 cm depth, the soil carbon stocks in Oxisols (61-71 Mg C ha^{-1}) were significantly higher than in Spodosols and Ultisols with higher sand content (46 and 42 Mg C ha^{-1}) (Telles et al., 2003). Overall, these studies indicate that soils with higher clay content in the region tend to store more carbon and for longer times.

Regarding CS and land use, in a forest degradation gradient in Santarém, western Pará, Brazil, undisturbed primary forest had the highest stocks of soil carbon, followed by secondary forest, while disturbance by fire significantly reduced soil carbon (Durigan et al., 2017). Soil carbon stocks were not affected by the conversion of primary forest to pastures but decreased significantly when conversion to cropland took place (Durigan et al., 2017). Along a similar forest degradation gradient in Paragominas, carbon stocks in aboveground vegetation, dead wood, litter and soil (upper 30 cm) decreased from undisturbed forest (276 Mg C ha^{-1}) to logged forest (238 Mg C ha^{-1}), logged and burned forest (187 Mg C ha^{-1}) and secondary forest (125 Mg C ha^{-1}) (Berenguer et al., 2014). Furthermore, Sommer et al. (2000) reported significant changes in soil carbon and root biomass after undisturbed forest (196 Mg C ha^{-1}) was converted to annual cropping agriculture (146-167 Mg C ha^{-1}), but no significant difference when converted to slash and burn agriculture (185 Mg C ha^{-1}). Data from these studies indicate that there are major differences in the amount of carbon undisturbed forests store as compared to croplands. Intermediate values are reported for other land uses.

Soil texture in combination with climate and management are also important factors influencing the activity of soil macro-fauna that produce biogenic structures (Brussaard et al., 2007). Moreover, soil texture also has been reported to be an important regulator of microbial communities in the soil after deforestation. For instance, Crowther et al. (2014) found that clayey soil textures act as a buffer for micro-organisms against altering soil moisture conditions, pH, and nutrients concentrations that may result from forest removal. They reported minimal differences of microbial communities between forest and grassland soils in eleven sites across the United States. The same authors compared their results in the United States to those of Rodrigues et al. (2013) who found that the mean bacterial richness in the soil increased by 47 taxa after forest clearance in the western Amazon region. Crowther et al. (2014) found that the species richness of bacteria in the clayey Brazilian soils is relatively stable across sites with different clay textures. These results point at the apparent protective effect of clay textures to micro-fauna even after deforestation. Furthermore, Hassink et al. (1993) reported a higher grazing pressure by nematodes on bacteria in sandy soils than in clayey soils, which in turn was linked to higher N mineralization rates per bacterium. It is recognized that micro-organisms, such as bacteria, might stimulate nutrient cycling, as many are considered to be keystone species (Lupatini et al., 2014). As in the case of CS, clayey textures and their higher soil organic matter content appear to provide protective effects to both soil micro- and macro-fauna.

Concerning HB and land use, the α-diversity of birds, dung beetles, orchid plant bees and ants declines from a gradient of undisturbed forests to mechanized agriculture in Paragominas (undisturbed primary forest > logged primary forest > logged and burnt primary forest > secondary forest > pastures > mechanized agriculture) (Solar et al., 2015; Solar et al., 2016). In addition, Barlow et al. (2016) reported that forest fragmentation and disturbance was associated with the loss of 46-61% of the biodiversity conservation value of forests in Paragominas. Rodrigues et al. (2013), found that in the western Amazon region bacterial communities were significantly higher in α-biodiversity in pasture soils than in forest soils. Nevertheless, the opposite was the case for β-biodiversity (i.e., differentiation across space) suggesting a process of biotic homogenization after forest conversion that leads to endemism loss and invasion of broad range taxa. Conversion of primary forests to pastures also has been found to reduce fungal richness and affect community fungal composition of specialized species in the Amazon region (Mueller et al., 2016). These data were used in our study to estimate HB indices for land use (Table 2.1).

Table 2.1 Indices for carbon storage and habitat for biodiversity, based on values for indicators from secondary data.

Land use	Aboveground biomass C(Mg/ha)	Soil C (Mg/ha)	Total C (Mg/ha)	CC index	Standardized species richness	HB index	Reference
Undisturbed primary forest	204.8 ±13.4	43.0 ±2.5	247.8	1.00	0.83	1.00	Berenguer et al., 2014; Solar et al., 2015b
Logged primary forest	133.9 ±6.3	63.5 ±3.7	197.3	0.80	0.77	0.93	Berenguer et al., 2014
Logged and burned primary forest	88.7±6.1	60.8 ±3.5	149.5	0.60	0.67	0.81	Berenguer et al., 2014; Solar et al., 2015b
Forest plantations	80.0	50.8 ±3.9	130.8	0.53	0.47	0.57	Behling et al., 2011; Maquère et al., 2008; Solar et al., 2016
Secondary forest	49.7 ±5.9	60.3±4.3	110.0	0.44	0.59	0.71	Berenguer et al., 2014
Pasture (12yrs)	33.5 ±6.8	52.7 ±1.1	86.2	0.35	0.42	0.51	Guild et al., 1998; Durigan et al., 2017; Solar et al., 2015b
Cropland	-	46.2 ±1.4	46.2	0.19	0.25	0.30	Durigan et al., 2017; Solar et al., 2015b

We also used soil texture as an indicator of agricultural soil quality since clayey soils in the Paragominas region have a greater inherent fertility and water holding capacity, as well as slower rates of nutrient leaching than sandy soils. For this reason, mechanized annual cropping such as soybean, maize and sorghum production, and forest plantations are typically located on clayey soils, whereas sandy and gravel soils are used for pastures (Maquere et al., 2008; Pereira et al., 2011; Piketty et al., 2015). Due to this distribution, our assessment distinguishes areas of crop production located on the plateaus where clayey soils are predominant, areas of forest plantations located both on plateaus and on sandy valleys, and pastures located mainly in the sandy valleys.

The capacity of different land uses to produce soybeans, beef and wood products were assessed in terms of gross profit margin. In 2017, Paragominas soybean exports amounted a total of US$219 million (MDIC, 2018). On the other hand, operation costs of no-till, genetically modified soybean in different parts of Brazil ranges from US$112-132 ton^{-1} (Goldsmith, 2008; Babajev, 2012). These figures give an estimated production cost of $80 million (exported net weight of soybeans from Paragominas in 2017 was 604 thousand tons). Including transportation costs, estimated at 85$ ton^{-1} for Mato Grosso (Goldsmith, 2008) signifies a gross profit margin of around 40%. Concerning beef production, the herd in Paragominas consisted of 253 thousand heads in 2017, with an export revenue of US$12.2 million (MDIC, 2018). The total weight of exported frozen meat and edible offal in 2017 was 1,893 and 599 tons, respectively (MDIC, 2018). Using conversion factors of 61% for frozen meat and 42% for edible offal (Holland et al., 2014) we estimated a total of 3,156 tons and 1,437 tons of live weight, respectively. Taking 545 kg as an average weight for live animal means that the number of heads devoted for exports was around 11,000, equivalent to roughly 4% of the total livestock in Paragominas. The other largest fraction of beef production was destined to local processors in other municipalities such as Belém and Castanhal. Taking US$2 kg^{-1} (Globo, 2014) as a general market price in the region, signifies a revenue between US$ 290-320 million. Summing up exports and local market indicates that revenues from beef production in Paragominas amounts to roughly US$330 million. While no data were available on the fraction of the animals that are not exported and remain as livestock or as a commodity in the local market, Somwaru and Valdes (2004) reported a gross profit margin of 24% for beef production in Paragominas. Finally, exports concerning forest products including wood, wood products and charcoal amounted to a total of US$0.64 million in 2017 (MDIC, 2018). In the state of Mina Gerais, the gross profit margin of eucalyptus plantations was estimated at 57% during a period of 7 years equivalent to a mean yearly profit of 8% (de Lima Filho, 2014). Another feasibility study for eucalyptus plantations in the Amazon reported for a 5-year rotation plantation a profitability index ([Net Present Value + initial investment]/initial investment]) of 4.97. A profitability index larger than 1 indicates the financial attractiveness of a project; however, the payback period of a eucalyptus plantation in the Amazon is around 5-7 years when destined for pulp and 12 years when destined for energy. Other forest species such as paricá (*Schizolobium amazonicum* Huber ex. Ducke) are used in the region for plywood production with investment return periods of 7 years in Paragominas (Paula et al., 2014).

These economic data indicate that soybean has the highest supply of commodity production based on a 40% profit margin and a short period on return on investment (Table 2.2). Forest plantations can have a high profit margin (57%) but have a return-on-investment period ranging from 5-12 years. Therefore, we rank forest plantations as a medium supply of commodity production. Finally, beef production is ranked as low supply of commodity due to a relative low profit margin. Indeed, the greater profitability of soybean is one of the factors hindering beef production and restoration of degraded pastures in the eastern Amazon region (Santos et al., 2007). It is important to acknowledge that this classification depends on price volatility. Due to its inelastic demand soybean is considered as one of the most volatile agricultural commodities. Beef, in contrast, is much less volatile (OECD/FAO, 2018).

Table 2.2 Estimated revenue, production costs, gross profit margin, investment return periods, and relative level of production supply for the main commodities in Paragominas for the 2004-2018 period.

Commodity	Revenue (US$)	Production costs (US$)	Gross profit margin (%)	Investment return period (years)	Supply of commodity production	Reference
Soybean	220 M	~73M	~40	1	High	MDIC, 2018; Goldsmith, 2008; Babajev, 2012
Wood products	0.63 M (exports only)	-	~57	5-12	Medium	MDIC, 2018; De Lima Filo, 2014; Paula et al., 2014; Pereira et al., 2011
Beef	~330 M	-	~25	1	Low	MDIC, 2018; Babajev, 2012; Somwaru and Valdes, 2004

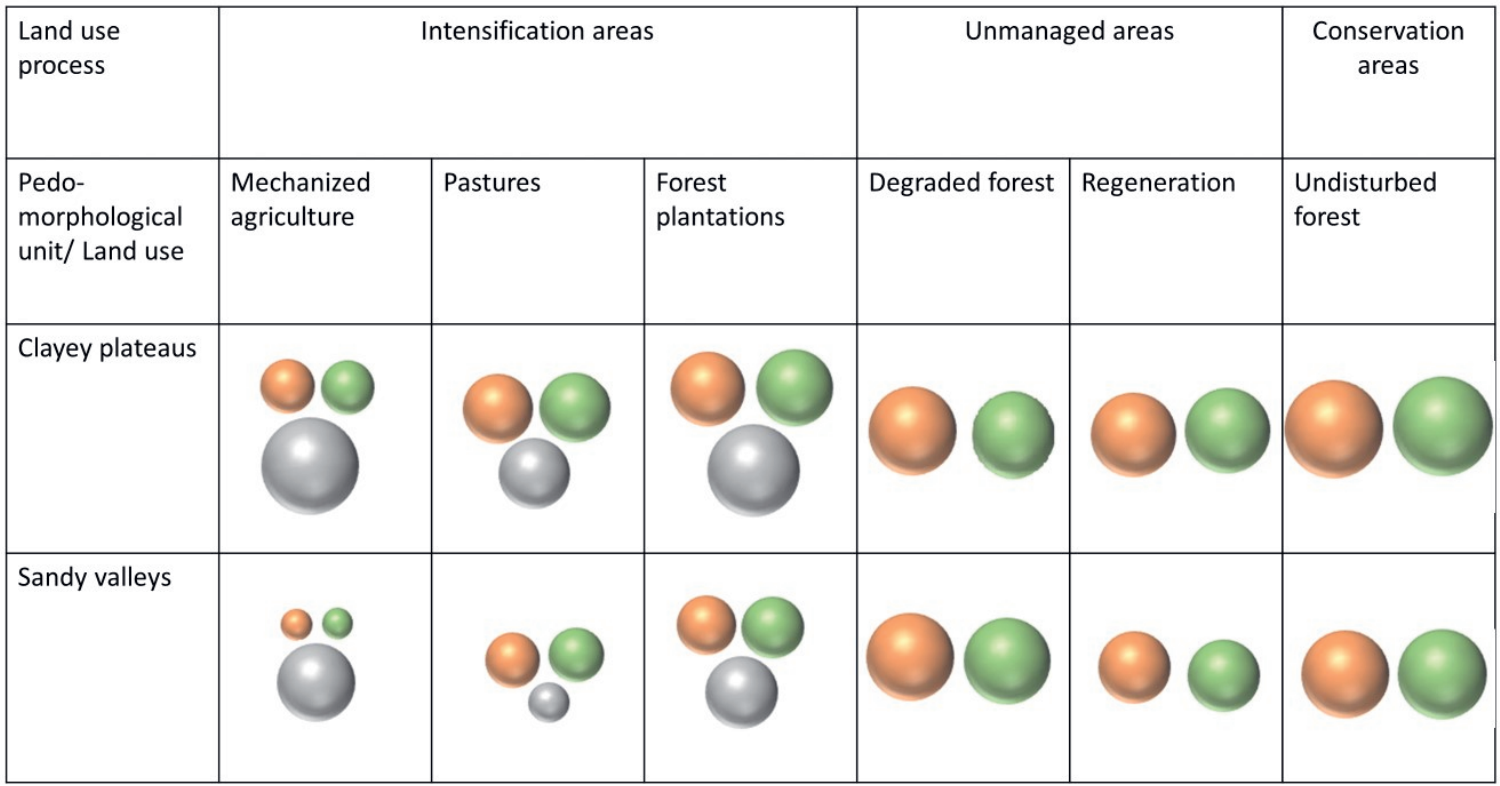

Figure 2.3 Supply matrix of ecosystem services in Paragominas for different pedo-morphological units and land uses associated with different land use processes. Supply of carbon storage (brown), habitat for biodiversity (green) and commodity production (grey) are indicated by bubbles, and bubble size is indicative for relative supply level. This analysis is informed by a literature review (Tables 2.1 and 2.2) and personal observations.

(Mis)match type	Supply	Relation	Demand	Trade-off type area
1	CP	<	CP	Nature
	HB	>=	HB	
	CS	>=	CS	
2	CP	<	CP	
	HB	<	HB	
	CS	>=	C	
3	CP	<	CP	
	HB	>=	HB	
	CS	<	C	
4	CP	<	CP	Suboptimal
	HB	<	HB	
	CS	<	CS	
5	CP	>=	CP	Multifunctionality
	HB	>=	HB	
	CS	>=	CS	
6	CP	>=	CP	Production
	HB	<	HB	
	CS	>=	CS	
7	CP	>=	CP	
	HB	>=	HB	
	CS	<	CS	
8	CP	>=	CP	
	HB	<	HB	
	CS	<	CS	

Figure 2.4 Overview of possible combinations of (mis)matches between carbon storage (CS), habitat for biodiversity (HB) and commodity production (CP), and associated trade-offs.

2.2.4 Demand for soil-based ecosystem services

National policies established in the Climate Change Policy (Lei 12.187/2009), the Plan for Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) and the Low Carbon Agriculture Plan (Plano ABC) of Brazil, include targets to reduce carbon emissions by 37% from 2005 levels by 2025, to end illegal deforestation, to restore 12 M ha of forest by 2030, to restore 15M ha of degraded pastures by 2030, and to implement 5 M ha of crop-livestock-forest integrated systems by 2030. At the state level, the Plan for Prevention, Control and Alternatives for Deforestation of Pará State (PPCAD-PA) translates this into a 42% reduction target for deforestation in the period 2016-2020 in relation to the previous period from 2011 to 2015.

Furthermore, the Green Municipality project in Paragominas advanced a zero-deforestation pact among an array of stakeholders since 2009, which was renewed in 2016 (Vilhena, 2016).

A crucial aspect for our analysis was to determine the implications of national targets at the local level in the absence of an explicit municipal target concerning carbon storage. Paragominas' agricultural sector gross domestic product represents less than 0.5% (US$95 million in 2016; (IBGE, 2018)) of the national agricultural primary sector estimated at US$77 billion in 2017 (Ministério da Agricultura Pecuária e Abastecimento, 2016). A calculation based on this proportion would equate to a target of 0.67-0.81 million tons CO_2eq for Paragominas (the mitigation potential of the national agricultural sector amounts to 133.9-162.9 M tons CO_2eq as estimated in Plano ABC). An estimation based on agricultural area results in a similar value of 0.5% of the total agricultural land in Brazil. These estimates show that based on these criteria, the national target would correspond to a municipal target in the order of magnitude of 0.7 M tons of CO_2eq. We did not further identify a spatial variation of this target within the municipality.

The demand for habitat for biodiversity was informed by the habitat requirements stated in the Forest Code (Código Florestal, Lei nº 12.651). It stipulates that all rural properties in the Amazon spare conservation areas known as Legal Reserves equivalent to 80% of the property and preserve all riparian forest (known as APPs, permanent conservation areas) within a distance of 30, 50, 100, 200 and 500 meters from rivers, depending on their length. An exception to this rule is contemplated in the Decree No. 7.130/2010, which concerns the Ecological-Economic Zoning. In practice this often means that Legal Reserves within productive areas make up for 50% of the farm. We framed the demand for HB in relation to the regularization plan of each rural property in order to comply with the 80/50% legal requirement.

Regarding the demand for CP, the state development plan, Plano Pará 2030, targets yearly increases of 15-18% and 2-4% for soybean and beef production until 2030, respectively. An important factor for delivering on the intensification of commodity production is market access (Piketty et al., 2015). Paragominas is located near the intersection of two interstate roads of which the federal road BR0-10 is a major transport route for agricultural produce. In recent years, mechanized agriculture and forest plantations have expanded predominantly in areas of clayey soils close to the Paragominas urban center due to easy road access (Piketty et al., 2015). We accounted for these trends by generating a map indicating traveling-time (areas of 1, 2-3, and >3 hours) to the city of Paragominas near the main interstate road (BR0-10) to distinguish areas where the demand to increase production is more likely to materialize. Such increases in

CP can only take place in areas already cleared since opening new forest areas is forbidden. We identified those areas, where the policy targets to increase production will be more likely to manifest in the landscape, by intersecting our traveling-time map with non-forested areas.

2.3 Results

2.3.1 Mapping the supply and demand for ecosystem services

We identified critical areas of carbon storage to mitigate carbon emissions from deforestation and forest degradation (Figure 2.5a). Using the Carbon Invest Model and secondary data, total C stocks in Paragominas in the soil and aboveground biomass were estimated at 279 million Mg C. Areas covered by undisturbed forests were estimated to store 247.8 Mg C ha^{-1}, while the lowest values were modelled for croplands (46.2 Mg C ha^{-1}). This indicates that undisturbed forests in Paragominas store 142 million Mg of carbon. Since the demand for CS has been downscaled from the national to the municipal level there is no spatial variation for demand of CS (Figure 2.5d).

Regarding the supply of HB, undisturbed forest supports the highest supply of HB (Figure 2.5b). These areas account for 36% of the total municipality. Areas of lower habitat quality are located mostly close to the city within one hour away from the main road where agriculture dominates the landscape. Concerning the demand, the total area of Legal Reserves and APPs stipulated in the regularization plans of farms in Paragominas adds up to 1.02 M ha (Figure 2.5e) and represents 52% of the municipal area. The total forest area in Paragominas is 56% (INPE, 2018), which suggests that in terms of forested area the demand for HB is met in the region.

Regarding CP, the highest supply in terms of gross profit margin takes place on clayey soils located near the main road with soybean production. Forest plantations, which provide intermediate supply, are also concentrated in the central area of the municipality, while pastures for beef production are mostly distributed to the east, in areas more than one hour away from the road (Figure 2.5c). Targets framed at the state level represent the demand to increase CP. In areas where mechanization and access to inputs and markets is less costly the demand is higher (Figure 2.5f). Nevertheless, considering the projected yearly increase of crop and livestock production up to 2030, intensification could also increase in more remote areas. Furthermore, the demand for CP could turn into pressure on forested areas that are located on clayey soils close to the city.

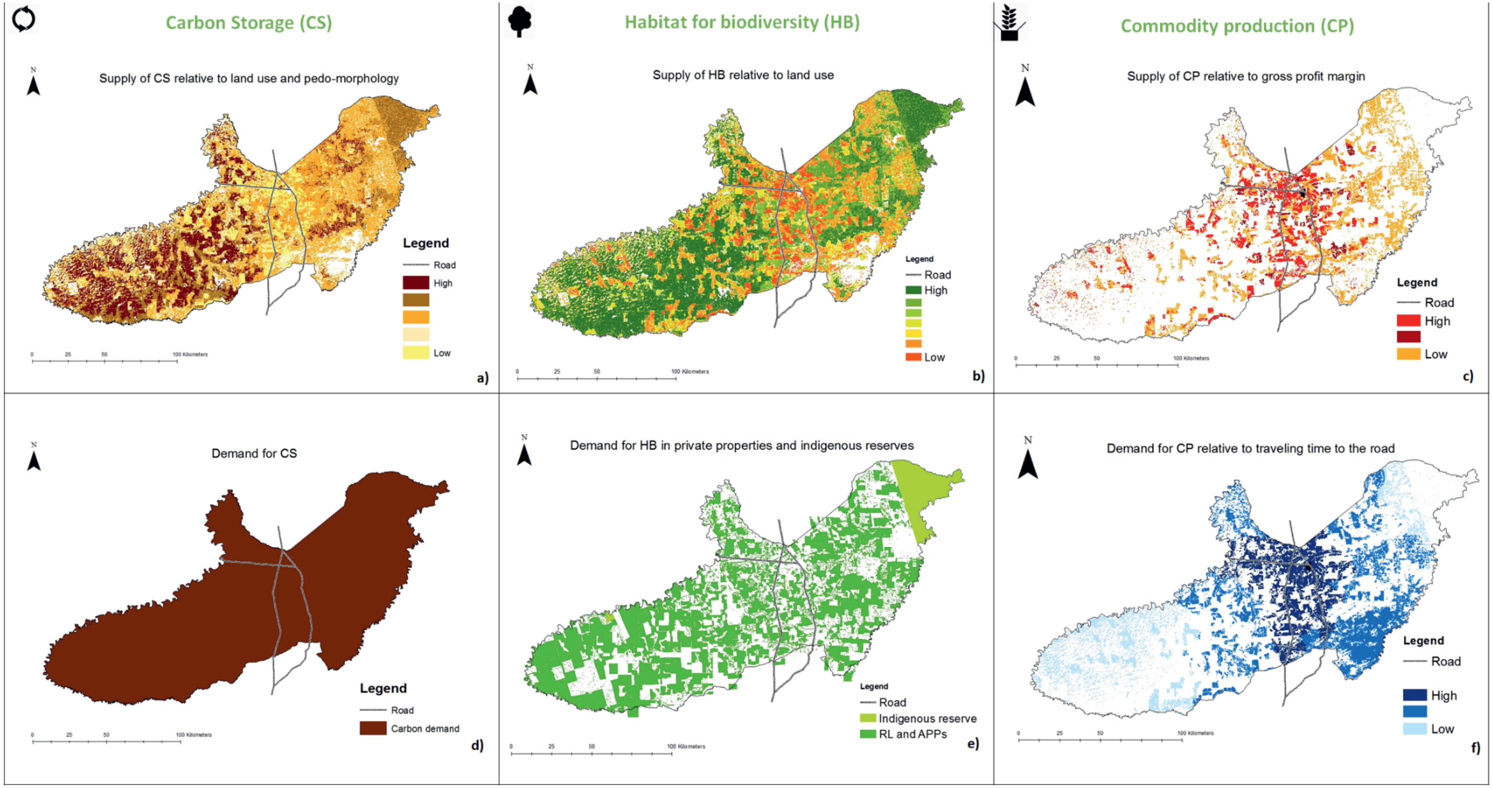

Figure 2.5 Maps of supply (top) and demand (bottom) of carbon storage, habitat for biodiversity and commodity production in Paragominas.

2.3.2 Potential spatial (mis)matches and trade-offs

Non-CP areas where the supply of CS and HB meet the demand (Mismatch type 1 in Figure 2.4) represent 32% of the analyzed area (Figure 2.6). These are areas covered by undisturbed forest on clayey plateaus and on sandy soils (i.e., "**Nature areas**" in Figure 2.6). "**Production areas**" (Mismatch type 8 in Figure 2.4) represent 18% of the area (shown in blue in Figure 2.6). These are pastures in sandy valleys and croplands on top of the plateaus. Here, CP is happening at the expense of CS and HB. "**Suboptimal areas**" (Mismatch type 4 in Figure 2.4 and indicated in red in Figure 2.6), represent 49% of the total area and are likely suboptimal for CP as these areas are mostly composed by pastures in floodplains and plateaus and agriculture in sandy valleys. These areas can also be sub-optimal for CS and HB because of forest degradation or abandonment (Figure 2.6). The identification of trade-off areas in conjunction with the supply-demand maps were the basis to identify possible pathways for landscape multifunctionality (Table 2.3).

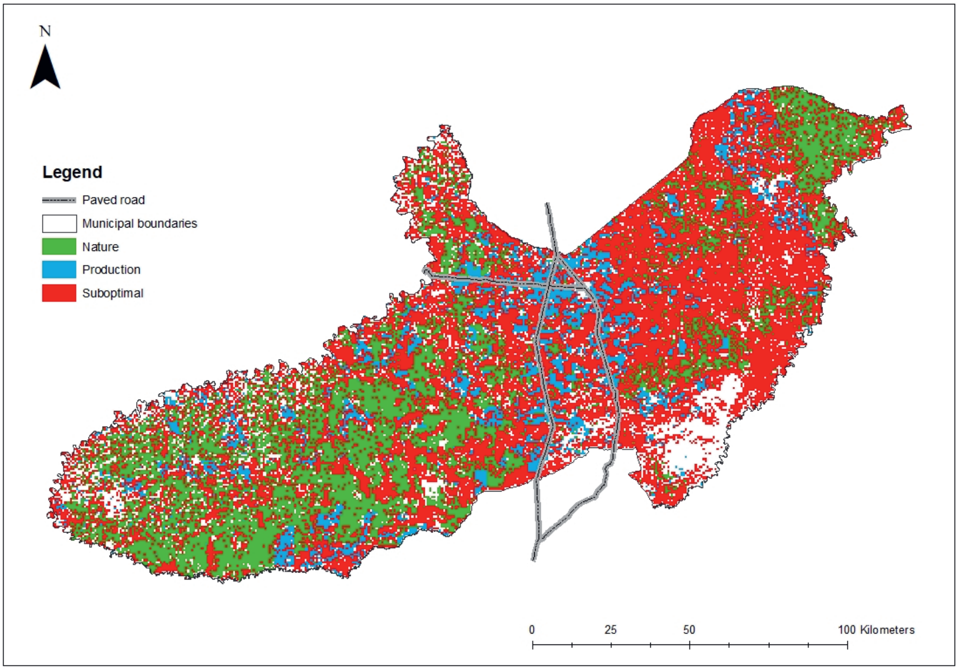

Figure 2.6 Areas of potential (mis)matches and trade-offs between ecosystem services according to pedo-morphological units and land uses in Paragominas.

2.4 Discussion

2.4.1 Meeting carbon storage and biodiversity conservation targets

Our analysis indicates that undisturbed forests fulfil the demand for carbon storage (Figure 2.5a). These critical areas, however, are located on clayey soils that are also suitable for grain production. Thus, even though extensive deforestation has been controlled and minimized in the region, these forests may face pressure in the near future due to forest degradation (Berenguer et al., 2014). Conversely, other land uses such as degraded pastures and croplands with lower carbon stocks offer potential to meet the further demand for carbon storage. For example, it has been estimated that land use conversion in the tropics, from cropland to pastures, to forest plantations and to secondary forests can increase soil carbon by 20-50% (Guo and Gifford, 2002). Similarly, restoring degraded pastures and implementing silvo-pastoral systems has a storage potential of 1.0 and 1.7 tons C ha^{-1} $year^{-1}$, respectively (Gurgel and Costa, 2015). Other studies suggest that integrated silvo-pastoral systems in the Amazon can store an additional amount of soil carbon (at 1 m depth) of up to 1.9 tons C ha^{-1}compared to extensive traditional pastures (Oliveira et al., 2018). Paragominas possesses 300,000 ha of degraded pastures that, if managed and restored, would represent a carbon storage potential of 0.3-0.5 M tons C $year^{-1}$ (Gurgel and Costa, 2015). This means that Paragominas could theoretically contribute its share of the national target (0.81 million tons of CO_2 eq) in only two to three years.

Concerning HB, in 2010, 56% of Paragominas was covered by forest (INPE, 2018), 51% consisted of primary forest (including degraded forest) and 5% of natural regeneration (Nunes et al., 2019). According to the Rural Environmental Registry (CAR), 67% of the rural properties of Paragominas comply with the Forest Code requirements, 31% have some pending issue and only 2% of the properties have been assessed as not meeting the requirements. If we compare these records with the available data from our literature review, we can notice that, for example, most of the rural properties located close to the main road comply with the legislation However, according to the secondary data it is precisely in these areas where the lowest levels of biodiversity can be found (Figure 2.5b). This suggests that the current legislation was not framed in the most pertinent way to effectively safeguard HB. Indeed, there is an increasing concern that Legal Reserves tend to be disconnected from the network of protected areas (Siqueira et al., 2018) because there are no explicit policy targets concerning forest habitat connectivity at the landscape scale that take into account forest patch size, patch shape, and landscape fragmentation (Oakleaf et al., 2017).

2.4.2 Landscape multifunctionality, (mis)matches and trade-offs

In this paper we argue that the trade-offs between ecosystem services in the region emerged from historical agrarian dynamics, i.e., colonization by pioneers from other regions of the country, characterized by land use changes that ignored key landscape characteristics. It is in this context that we envision a multifunctional landscape as one that matches supply and demand of different ecosystem services through synergistic interactions between multiple ecosystem services. However, attaining these synergies is difficult in complex agroecosystems and therefore FLM aims for the spatial optimization rather than the ubiquitous maximization of all ecosystem services (Schulte et al., 2015).

Our notion of landscape multifunctionality aligns with what Manning et al. (2018) define as ecosystem service multifunctionality as opposed to ecosystem function multifunctionality. The former concerns the supply of an ecosystem service according to the value assigned by human judgement, whereas the latter focuses on the ecological processes. Furthermore, following the classification of landscape multifunctionality proposed by Mastrangelo et al. (2014) (i.e., pattern-based multifunctionality, process-based multifunctionality, socially relevant process-based multifunctionality), our approach is based on a spatial approach in order to identify priority areas (i.e., trade-offs and mismatches) where interventions via land use change and management practices could be pertinent. However, we also integrate social elements by taking the policy framework as proxies of societal demands, and by considering aspects such as infrastructure and markets access. Additionally, our supply matrix (Figure 2.3) illustrates the concept of landscape multifunctionality in terms of natural processes linked to pedo-morphology and land use driving the supply of each ecosystem service. By applying the FLM framework we integrate elements of the main three multifunctionality categories defined by Mastrangelo et al. (2014) despite the constraints of primary data availability and direct stakeholder participation for ecosystem services selection.

Furthermore, our trade-off map integrates the analysis of CS, HB, and CP by dividing the region into three main types of landscape configurations (Figure 2.6). Suboptimal areas cover around half of the municipality but encompasses a variety of land uses and covers located in different pedo-morphological areas (Table 2.3). "Production" and "Nature areas" cover the other half of the region and are typically spatially separated, often located one hour away and more than three hours away from the urban center, respectively. We could conjecture that the spatial patterns of these two areas follow a land sparing arrangement. Phalan (2018) defines land sparing as the conservation intervention to increase agricultural productivity and free up land for habitat conservation. Areas of high-intensity practices in Paragominas are expected to be incompatible with biodiversity conservation (due to practices such as heavy use of pesticides) and tend to have a relatively coarse spatial grain (e.g., the average rural property size in the region is 800 ha). At the municipal scale, this results in an emergent pattern of relatively large areas with intensified agricultural production that are spatially separated from high quality habitats for biodiversity conservation. The caveat of this spatial arrangement in Paragominas is that a pure land sparing configuration in tropical contexts is generally followed by a transition to a cleared landscape (Angelsen and Kaimowitz, 2001b). Although environmental legislation in Brazil may prevent large-scale forest clearing, forest degradation and habitat disconnection may still be considered a threat to biodiversity conservation in the region.

Our spatially explicit categorization of landscape units and the (mis)matches and trade-offs between ecosystem services may guide the implementation of measures to reorganize the landscape. Our analysis is based on what Driscoll et al. (2013) denominates the “patch-matrix model” of fragmented landscapes, i.e., patches of native vegetation surrounded by a highly modified matrix due to agriculture. Our analysis points out the importance of managing this matrix to match supply and demand of ecosystem services. Specifically, for biodiversity, the same authors suggest that managing the matrix in a fragmented landscape can have effects on movement and dispersal, resource availability, and the abiotic environment. Therefore, one strategy in Paragominas should be to make the matrix structurally more similar to the remaining forest patches. In this way the landscape could benefit from incorporating a land sharing approach in “Production” areas to increase forest connectivity in order to enhance species dispersal, food availability and improve microclimatic conditions. This could also be the case for some “Suboptimal” areas where forest enrichment, reforestation, afforestation, or the incorporation of integrated systems such as silvo-pastures or agroforestry could be designed towards a land sharing approach. A focus on the catchment level may be required to explore new conservation strategies that take into account matrix heterogeneity in space and time, and adaptation of species to changing landscape conditions (Driscoll et al., 2013). Such measures to make the matrix resemble patches of natural vegetation could simultaneously increase the supply of carbon storage.

On the other hand, a land sparing format for biodiversity conservation could be kept in “Nature areas” and in “Suboptimal” areas that are unsuitable for agricultural production. This mosaic of land sharing/sparing based on our maps could reconcile what some authors point out as the false dichotomy between land sharing and sparing (Renwick and Schellhorn, 2016). Kremen (2015) calls this a “both-and” design characterized by the establishment of large protected areas able to host endemism and specialist species, and a matrix of agricultural landscapes surrounding conservation areas allowing for species dispersal and room for human activities.

2.4.3 Pathways to match supply and demand of ecosystem services

Following this “both-and” logic, we distinguish two pathways to match supply and demand of ecosystem services, while minimizing trade-offs in Paragominas. A first pathway centers on agricultural management at the field scale. For example, land for soybean production under conservation agriculture practices is expected to yield different results on the supply of CS or HB compared to soybean monoculture under conventional practices (Corbeels et al., 2006; de Pontes et al., 2017). Thus, a farmer aiming to increase grain production on a clayey plateu can adopt intensification measures such as precision agriculture, no-tillage, or crop-livestock integration to increase commodity production without compromising the supply of CS and HB (Corbeels et al., 2006; Maia et al., 2010; Sentelhas et al., 2015; Gil et al., 2016). A second example includes pastures that are integrated into silvo-pastoral systems to increase the production of meat and timber, while at the same time increasing CS and HB. Tree-livestock-crop integrated systems may foster positive interactions between different ecosystem services and resource-use efficiency in the Amazon and the Cerrado (Campos et al., 2015; da Conceição et al., 2017; Stark et al., 2017; Gil et al., 2018). Considering the supply matrix (Figure 2.3), this pathway means that within a landscape unit (e.g., mechanized agriculture on clayey plateaus) the supply of all ecosystem services can be increased (i.e., the size of the bubbles) by adopting management practices that modify soil properties as well as energy, nutrient and water fluxes at the field and farm level. This in turn, can lead to an agricultural matrix that resembles as much as possible the ecological functionality of the forest. Importantly, the absence of management as a result of abandonement can also play a role in the supply of ecosystem services in the region. For instance, unmanaged pastures can lead to natural regeneration and subsequent increases in botanic biodiversity (Poccard-Chapuis et al., 2014). Conversely, the absence of management of degraded forest can have detrimental effects on carbon stocks due to the incidence of forest fires (Berenguer et al., 2014).

A second pathway concerns land use changes. In terms of the supply matrix (Figure 2.3), this implies a displacement from one landscape unit to another, e.g., from natural regeneration in clayey soils to crop land on clayey soils. These land use changes should aim at increasing forest connectivity. Under this scenario, trade-offs between CP and CS-HB are minimized by prioritizing conservation in selected areas that have less potential to produce commodities (i.e., "Suboptimal" area). Suboptimal areas where production has less potential (i.e., natural regeneration in sandy valleys close to water bodies) could also be prioritized for conservation to minimize trade-offs at the landscape scale. This pathway, however, has the challenge of managing at a higher scale than the farm, the main operational level of functional organization in the region (Poccard-Chapuis et al., 2014).

A critical point for optimizing ecosystem services is to distinguish where to follow which pathway. This revolves around the question of where the clayey soils, roads, forests and cleared areas are located because this will determine the aptitude of a particular area to perform certain ecosystem service. Therefore, optimization of the landscape means that intensification activities with emphasis on integrated systems should be placed in open areas without forests located on plateaus and in valleys ("Production" areas and "Suboptimal" areas with natural regeneration). These areas account for 20-25% of the municipality. Reforestation should be prioritized to increase forest connectivity in areas with low production potential, such as "Suboptimal" areas on floodplains (10-15% of the municipality). "Nature" areas (a third of the total area) should be kept protected, while forest restoration should be implemented in areas of forest degradation with low production potential covering between 10-15% of the territory. This leaves between 15-20% of "Suboptimal" areas with degraded forest located on plateaus or in valleys that could have potential for production or forest restoration (Table 2.3).

As pointed out by Schulte et al. (2015), it is important to acknowledge that FLM is not a call for a top-down approach to impose a zoning in the region. Rather, we intend to offer tools that foment land use planning discussions that go beyond the farm level and take into consideration biophysical aspects that require a landscape approach, for example, at the catchment level. The development and implementation of pathways through the identification of trade-off areas may involve a complex governance challenge that requires the engagement of all relevant actors in the region. Given the recent success story of a societal agreement towards environmental compliance in Paragominas through the "Green Municipality" project (Viana et al., 2016), the region appears in a good position to embark in such a task.

The development of these pathways is the subject of further research under the approach of what Huppes and Ishikawa (2007) define as environmental cost-effectiveness; that is, an environmental prime as the criteria to rearrange the landscape. These could potentially counter the "artificialization" of the landscape in Paragominas (Poccard-Chapuis et al., 2015) and move towards more endogenous landscape systems that are better at fulfilling the demands for ecosystem services in a way that is both ecologically and economically sustainable. One of the main challenges in this regard is to make the jurisdictional approach operational to attain landscape governance given the diversity of scales, actors, and demands (Pacheco et al., 2017). What are the options within conventional, resource-intensive agriculture to introduce spatial changes oriented towards the transition of food systems? Can land use planning offer a way to contribute to this transition? Does matching the supply and demand of ecosystem services offer a model of ecological intensification in a tropical post-forest frontier? As pointed out by Tittonell (2014), processes of ecological intensification require a landscape approach that takes nature as an active ally. Contrasting the supply and demand for ecosystem services offers a hint of what the current role of nature is in the landscape of Paragominas and the possible pathways to be implemented at the farm level to "work with nature" and attain landscape multifunctionality.

Table 2.3 Pathways to optimize ecosystem services in Paragominas in terms of current land use and pedo-morphological unit.

Trade-off type area	Current land use	Pedo-morphological unit	Pathway	Approximate area subject to this pathway (1000 ha)
Production	Pastures, agriculture	Plateaus, valleys	Intensification through integrated systems	250
Nature	Undisturbed forest	Plateaus, valleys	Conservation	700
Suboptimal	Pastures, agriculture	Floodplains, duricrust layer, erosion incisions	Reforestation	300
	Unmanaged natural regeneration	Plateaus, valleys	Intensification through integrated systems	200
	Unmanaged degraded forest	Plateaus, valleys Floodplains, duricrust layer, erosion incisions	Forest restoration or intensification through integrated systems	500

2.4.4 Limitations

A few limitations in our approach emerge from our conceptualization of landscape multifunctionality. First, we established a (mis)match in terms of policy targets that we take as a proxy of societal demands (Schulte et al., 2015). These targets were established at federal and state level and do not necessarily reflect the actual demand and use of ecosystem services by local stakeholders. In the original case study conducted in Ireland, FLM takes policy targets as societal demands as Ireland has policies explicitly stating agricultural and environmental targets. However, the representativeness of policies in a relatively small country like Ireland as compared to a country with continental scales such as Brazil can vary greatly. For example, in 2018, the Economist Intelligence Unit's Democracy Index placed Ireland in the 6th place worldwide with a score of 8.33 for political participation, while Brazil ranks number 50 with a score of 5.00 (The Economist Intelligence Unit, 2019). Assuming the same policy-making process in such a different context as Brazil can be misleading but given the complexity of all the different governance layers that affect land use in the Amazon region, these policy targets become a useful starting point to examine the relationships between international, national, and local demands that shape the landscape of Paragominas. This paper thus, does not consider direct stakeholder participation because it attempts to provide an overarching panorama of the landscape in terms of ecosystem services and environmental policies. Further studies on the comparison of policy targets and the perception and actual demand of ecosystem services by stakeholders could provide valuable insights to what extent demands for ecosystem services at policy levels align with demands by other stakeholders.

A second limitation of our study is that we considered only three ecosystem services. The selected ecosystem services have the advantage that their supply can be upscaled with a reasonable degree of reliability from a landscape unit to the whole landscape. Other ecosystem services, such as nutrient cycling, water regulation, pollination and pest control and cultural ecosystem services are equally important but involve spatial aspects or complexities that make upscaling from plot to landscape level fraught with uncertainties (Manning et al., 2018). For example, insect-mediated ecosystem services, such as natural pest control is governed by the dispersal ability and behavior of natural enemies, which are species-specific and hard to generalize (Karp et al., 2018). Ecosystem services associated with water and nutrient flows pertain complexities, such as vertical distances from tree to soil, livestock mobility, and surface infiltration (Poccard-Chapuis et al., 2014; Lavelle et al., 2016). Cultural ecosystem services are often bundled with food values and are difficult to localize and to correlate with other ecosystem services (Cooper et al., 2016). Our three focal ecosystem services on the other hand, can be quantified at large spatial scales and enables identifying "pressure points" (i.e., mismatches) at relevant spatial scales for policy making.

A third limitation of this study is our reliance on only secondary data. By restricting our literature review on studies from the Amazon and Cerrado biome we harnessed the context-specificity of CS and HB data as much as possible. The supply of CP was estimated in part from studies from more remote areas and from different years over the last 15 years. Our results, therefore, should be interpreted with caution, and used as indicators of spatial patterns (i.e., areas of trade-offs between ecosystems), rather than interpreted as geo-referenced quantification of ecosystem services.

2.5 Conclusions

In this paper we defined landscape multifunctionality in terms of the values that are assigned to different functions by different stakeholders. However, the landscape of Paragominas is conditioned by different sets of values: from environmental to productivity-oriented, from global to local, from a desire to urbanize to a call for pristine wilderness in the region. How can the landscape satisfy all these values?

Combining land sparing and sharing formats can generate a multifunctional mosaic that satisfies as much values as possible in line with the philosophy of Functional Land Management. This could also provide enough flexibility to cope with the bio-physical heterogeneity, while considering aspects such as land tenure and accessibility. This strategy, however, may require that conservation areas be delimitated beyond the boundaries of a single rural property (e.g., the watershed level).

Ultimately, the multifunctionality of the landscape ought to be constructed by the decision makers of the region who are local farmers in the first place deciding based on individual values. In this paper we provide a delimitation of three areas at the municipal level characterized by different trade-offs between ecosystem services. This is intended as a source of terms, concepts and data, around which stakeholders can gather around, and engage in a complex decision-making process towards enhancing landscape multifunctionality in Paragominas.

2.6 Acknowledgements

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Chapter 3

Characterizing farm diversity in the eastern Amazon region: implications for agricultural intensification in a transitioning frontier

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In preparation

Abstract

Agricultural intensification in conjunction with forest conservation may offer a pathway to harness agricultural production and preserving biodiversity and associated ecosystem services in tropical countries. In the Brazilian eastern Amazon region, a combination of forest conservation policies, public-private coalitions, and infrastructure development projects in the early 2000s prompted a shift towards agricultural intensification and environmental compliance which achieved an historic deforestation reduction during the 2004-2014 period. Nevertheless, recent spikes of deforestation in the Amazon have casted doubts on the effectiveness of those command-and-control measures for the long term. In the municipality of Paragominas in Pará State, controlling large scale deforestation began in 2008 after a local initiative i.e., Green Municipality, forged a pact among landholders to end large-scale deforestation and monitor private forests within farms (i.e., Legal Reserves). This low-deforestation context has induced agricultural intensification in Paragominas to increase production in cleared land. However, there is limited understanding on how agricultural intensification is unfolding in farms in Paragominas. We tackle this knowledge gap by conducting surveys via interviews in 40 medium and large-farms and develop a farm typology based on farm structural variables. We identified three farm types: 1) Extensive cattle-soy ranches (n= 7), which used to be traditional cattle ranches that have gradually converted pastures to soybean monocultures and thus tend to be a mix of pastures, cropland, and forests; 2) Integrated farms (n=9), focusing on integrated agro-pastoral systems and are run by the wealthiest agribusiness firms in the region; and 3) Soybean-based farms (n=24), specializing on soybean production. Soybean-based farms comprise small farms close to paved roads, as well as large farms in remote areas. Our farm typology suggests a range of agricultural intensification based on soybean production and agro-industrial practices. Understanding how these practices unfold can be useful to conceive and implement novel farm agricultural diversification pathways as an intensification strategy to minimize trade-offs between agricultural production and forest conservation.

Keywords: Farm diversity, agricultural intensification, agricultural diversification, land sparing, eastern Amazon

3.1 Introduction

Agricultural intensification, entailing the increase of production per unit area by increasing inputs and intensifying management, was a term coined in the early 1960s and formed an integral part of the so-called Green Revolution. This propelled large increases of global agricultural productivity accompanied by a decrease of world hunger from 60% to less than 20% of the world population in a time span of 40 years (Borlaug, 2007). Proponents of agricultural intensification have claimed that during the first 50 years since the Green Revolution, agricultural intensification halted the conversion of natural areas into agricultural land, avoiding the release of 161 gigatons of carbon emissions into the atmosphere (Burney et al., 2010). These claims sparked the land sparing hypothesis that postulates that agricultural intensification can reduce land pressure from natural land as farmers can produce the same amount of food on a smaller area. A counter argument, however, is that the profitability and efficiency gains resulting from technological advances incentivizes further agricultural expansion into natural areas, fueled by an increasing global food demand i.e., the Jevons' paradox (Alcott, 2005).

In the Brazilian Amazon, a 70% reduction in deforestation was paired with an increase in cattle and crop production between 2004-2014 (PRODES, 2017). These developments led to arguments suggesting that improved forest conservation policies that constrain agricultural expansion can stimulate agricultural intensification, in line with the land sparing hypothesis (Koch et al., 2019). However, these measures to halt deforestation coincided with declining prices of soy and beef in the international market making it hard to pinpoint the causal factors underlying deforestation reduction in this period (Fearnside, 2017b). Moreover, recent spikes of annual deforestation and forest degradation confirm that agricultural intensification is not decoupled from deforestation in the Amazon region (Gibbens, 2019; Fonseca et al., 2020).

Forest conservation policies and measures eliciting land constriction to limit agricultural expansion into forests prompted agricultural intensification mostly in the form of soybean monocultures in available open areas that were cleared during the colonization phase (Nepstad et al., 2014; Thaler, 2017). Nevertheless, from an ecological and social perspective, traditional models of agro-industrial intensification are not sustainable nor eco-efficient (Tittonell, 2014). Industrial agricultural practices are often a driver of the simplification of agro-ecosystems with the concomitant biodiversity loss and reduction in the supply of ecosystem services (Kremen and Miles, 2012). Industrial agriculture also foments dependence on external agrochemical inputs that may contribute to soil degradation, eutrophication, greenhouse gas emissions and pollution (Kremen and Miles, 2012). Therefore, there is a need to develop models of ecological intensification based on diversification at large-scale (Tittonell, 2014; Kremen, 2020). Agricultural diversification entails the diversification across ecological (e.g., genetic diversity of crops, intercropping, semi-natural communities in hedgerows and riparian buffers), spatial (e.g., agroforestry, mosaic of crop types and land uses) and temporal (e.g., asynchronous tilling and planting while tree cooping systems sustain process of ecological succession) scales for maintaining and regenerating biotic interactions that sustain ecosystem services (Kremen and Miles, 2012). This in line with the concept of ecological intensification which refers to the use of natural processes to replace artificial inputs like pesticides and fertilizers while maintaining or increasing productivity (Kremen, 2020).

In order to develop novel models of ecological intensification in the eastern Amazon region, it is helpful to characterize the diversity of current farming systems[3]. Currently, there is limited understanding on how agricultural intensification unfolds, and whether this process gives rise to differential trajectories of farming system development in the region (Poccard-Chapuis et al., 2014). The artificial stratification of farms (i.e., farm typology) is a practical way to capture and assess farming systems complexity and diversity (Alvarez et al., 2014; Kuivanen et al., 2016). Therefore, in this paper we aim to assess the diversity of farming systems in the eastern Amazon region by developing a farm typology. We take an inductive approach to develop a structural farm typology based on resource endowment and historical trajectory to assess agricultural intensification. The outcomes of this study can inform the development of farm intensification pathways to increase productivity, recovering degraded land, diversifying agricultural production and reconcile agricultural intensification and forest conservation in the long run in the eastern Amazon region.

3.2 Materials and methods

3.2.1 Study area

The municipality of Paragominas in the state of Pará is one of the most advanced forest frontiers in the eastern Brazilian Amazon, potentially heading towards a stabilization of the agricultural frontier (Poccard-Chapuis et al., 2014). The municipality was founded in 1965 after the completion of the Belém-Brasilia highway in the early 1960s (Veríssimo et al., 1992). In the early 2000s, after a long history of intensive logging and extensive cattle ranching in the region,

[3] Farming systems can be defined as a decision making unit comprising a household/manager, and cropping and/or livestock subsystems that transform land, capital and labour into agricultural products or commodities (Fresco and Westphal, 1988).

the federal Plan for Deforestation Prevention and Control, elicited a combination of private and public measures including heavy fines for forest clearing that compelled farmers to abandon extensive and extractive production methods that prevailed in the region (Nepstad et al., 2014; Poccard-Chapuis et al., 2014; Piraux et al., 2019).

This transition towards agricultural intensification entailed a shift in agricultural practices from slash and burn cultivation and extensive cattle ranching to the gradual adoption of novel agricultural technologies, such as the use of chemical fertilizers and pesticides, genetically modified soybean and maize crops, liming of pastures, and the integration of agriculture and livestock systems (Poccard-Chapuis et al., 2015). Furthermore, in 2008 a local social pact led by the Municipal Government and rural elites was signed to end deforestation giving the region the title of the first "Green Municipality" in the Amazon, an initiative that the State Government would then reproduce across Pará (Piketty et al., 2015). Given this context of controlled large-scale deforestation, farm dynamics in Paragominas became driven by the need to increase agricultural productivity on existing agricultural land and by the obligation to maintain forest cover in permanent preservation areas (forests areas along rivers and hilltops), and maintain 50-80% forest cover within farms (i.e., Legal Reserves) as mandated by law (Poccard-Chapuis et al., 2015).

In Paragominas, 95% of the territory is covered by private lands (Brandão et al., 2020), and it has one of the highest levels of agricultural land concentration in the region (Simmons et al., 2002), with an average farm size ranging between 800-1000 ha (Viana et al., 2016). The natural vegetation in the region is characterized by evergreen, lowland rainforest. The climate is tropical monsoon (Am, Koppen Classification) with an annual average temperature of 26 °C and an annual average precipitation of 1,750 mm (Alves et al., 2014). Oxisols are the prevalent soils while the relief is shaped by clayey plateaus (100-220 m.a.s.l,) separated by valleys (5-15 km wide) of loamy sands (45-80 m.a.s.l) shaped by a dense network of water bodies (Laurent et al., 2017).

3.2.2 Data collection

We surveyed 40 farms in March 2017 (7 farms) and April 2018 (33 farms). The farms were selected from the public database of the municipal Environmental Rural Registry (CAR for its acronym in Portuguese) by generating a random sample of private farms. We excluded farms inside (smallholdings) colonist settlements since our focus was medium and large farms (i.e., fazendas) that cover the largest part of Paragominas, and because arguably federal policies have had the strongest impact on agricultural intensification through land constriction on these landholdings. This resulted in a list of 40 medium and large farms with their registration code and location. In the case that the farmer was not reachable at the selected farm, we approached the neighboring farm. Our farm surveys were conducted using a questionnaire focused on structural variables, including area size, leased area or area on lease, effective production area, proportion of Legal Reserve on the farm, unproductive area, age of the farm, area of each production system, herd size, cattle density, and labor intensity (Table 3.1). From our interviewees, 39 farmers were male, and one was a female farmer. In 36 out of 40 cases, the interview was conducted with the owner of the farm. In the rest of the four interviews, the interview was conducted with the manager of the farm.

3.2.3 Data analysis

To generate a typology of farms, survey data were analyzed using principal component analysis (PCA) to reduce the dimensionality of the dataset and characterize the structure of the data. To select the number of principal components (PCs), we applied Kaiser's criterion (i.e., retain PCs with an eigenvalue higher than 1.00) while having a cumulative percentage of variance higher than 60%. The second step was to conduct a hierarchical, agglomerative cluster analysis using Ward's method (Alvarez et al., 2014). We conducted this agglomerative nesting process by developing a dendrogram. The number of clusters was defined by minimizing this number, while maximizing both intra-cluster homogeneity and inter-cluster heterogeneity. For the PCA we used the package *FactoMineR* (Lê et al., 2008) and cluster analysis was conducted with the *cluster* package in R v4.1 (Maechler et al., 2019).

3.3 Results

3.3.1 General description of farms

The average farm size was 3,310 ha, but there was high variation (Table 3.1). All the farms produced soybean (*Glycine max*) for export and/or beef for local markets. Half of the farms near Paragominas city (less than 60 minutes by car) were oriented towards soybean production due to good access to the market, agricultural inputs, and machinery, facilitating intensive agricultural practices. Farms at distances further than 1-hour drive from the urban center showed higher variation in farm size and production orientation (see below).

3.3.2 Heterogeneity of farm structural variables

The PCA resulted in the extraction of five principal components (PCs) explaining 67% of the variability in the data set (Table 3.2). The first component (PC1) correlated highly with total farm area, effective production area (Prodarea), and herbicide and limestone use intensity. Thus, PC1 mainly related to capital for intensification (Figure 3.1a and 3.1e). The second component

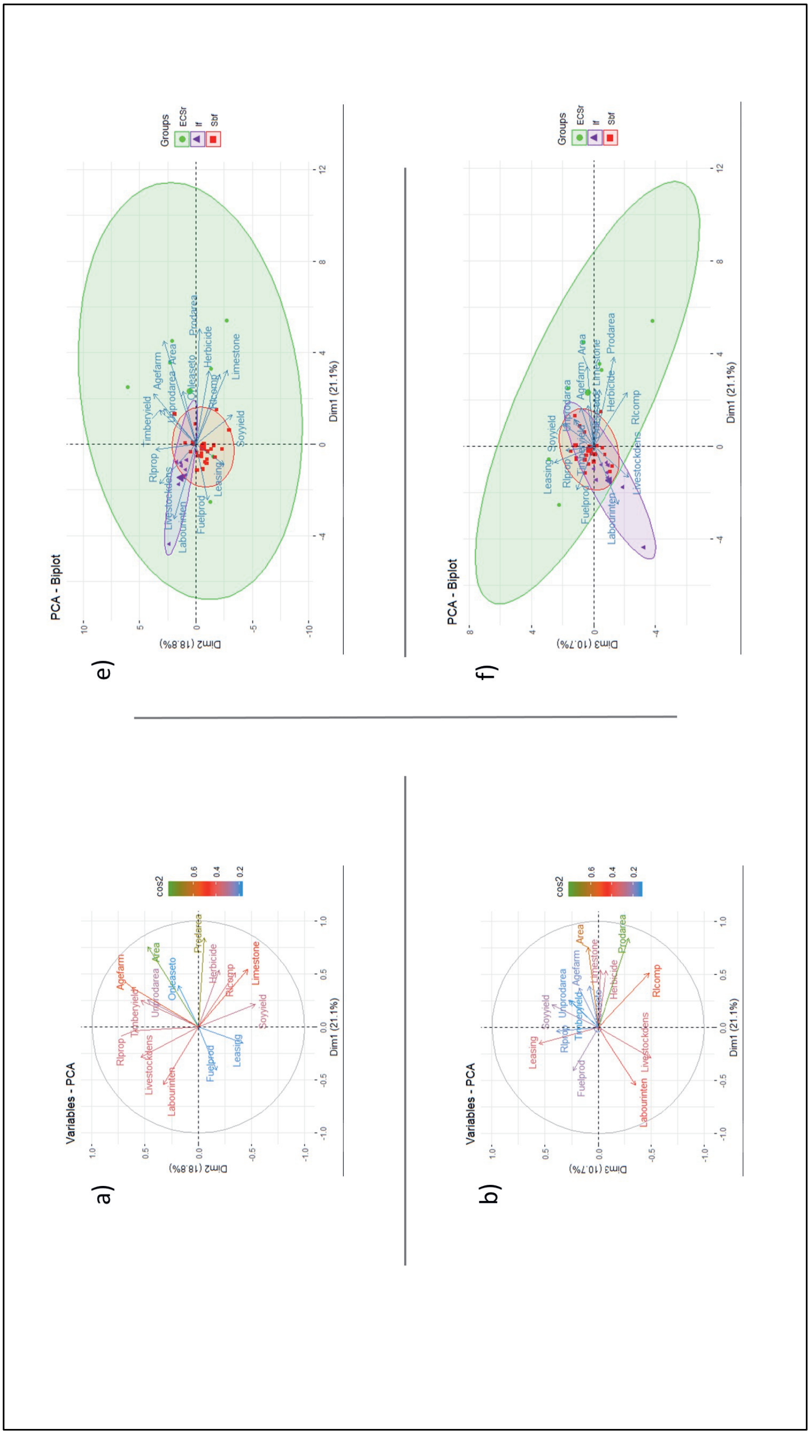
(PC2) was related to the proportion of the Legal Reserve on the farm (Rlprop), but also to the age of the farm and cattle density (Fig. 3.1a and 3.1e). The third component (PC3) described leased areas from other farms for production (Leasing) or for acquiring Legal Reserves (Rlcomp) in case no forest was left on the farm (Fig. 3.1b and 3.1f). The fourth and fifth principal component each explained less than 10% of the variance and were related to labor intensity, fuel consumption and leased area to another farm (Figures 3.1c and 3.1g, and 3.1d and 3.1h, respectively). The reduced data set of five PCs was the input for the cluster analysis, which resulted in three clusters entailing 7, 9 and 24 farms, respectively (Figure 3.2).

Table 3.1 Structural farm variables used to construct a farm typology of 40 medium and large farms in Paragominas.

Variable	Unit	Mean	Standard deviation	Min.	Max.
Farm area	ha	3,310	4,862	28	21,000
Leased area for production	ha	424	913	0	4,500
Area on lease (to another farm)	ha	53	244	0	1,500
Production area	ha	1,480	2,208	18	11,000
Proportion of Legal Reserve on the farm	%	38	25	0	80
Leased area of Legal Reserve	ha	434.8	1,769	0	10,000
Unproductive areas (fallow or degraded, abandoned agricultural land)	ha	67.5	168	0	700
Age of the farm	year	13	9	1	40
Soybean area	ha	913	1,486	0	8,000
Herd size	animal heads	600	1,124	0	5,730
Cattle density	animal heads/ha	0.5	0.8	0	3.2
Labor intensity	employees/ha (production area)	0.01	0.02	0.0	0.11

Table 3.2 Eigenvalues and percentage variance explained by five principal components (PCs).

PC	Eigenvalue	Variance (%)	Cumulative Variance
1	3.1	21.1	21.1
2	2.8	18.8	39.8
3	1.6	10.7	50.5
4	1.3	8.8	59.4
5	1.2	7.8	67.1


a)
Variables - PCA
Dim1 (21.1%)
Dim2 (18.8%)
cos2
b)
Variables - PCA
Dim1 (21.1%)
Dim3 (10.7%)
cos2
e)
PCA - Biplot
Dim1 (21.1%)
Dim2 (18.8%)
Groups
ECSr
If
Sbf
f)
PCA - Biplot
Dim1 (21.1%)
Dim3 (10.7%)
Groups
ECSr
If
Sbf

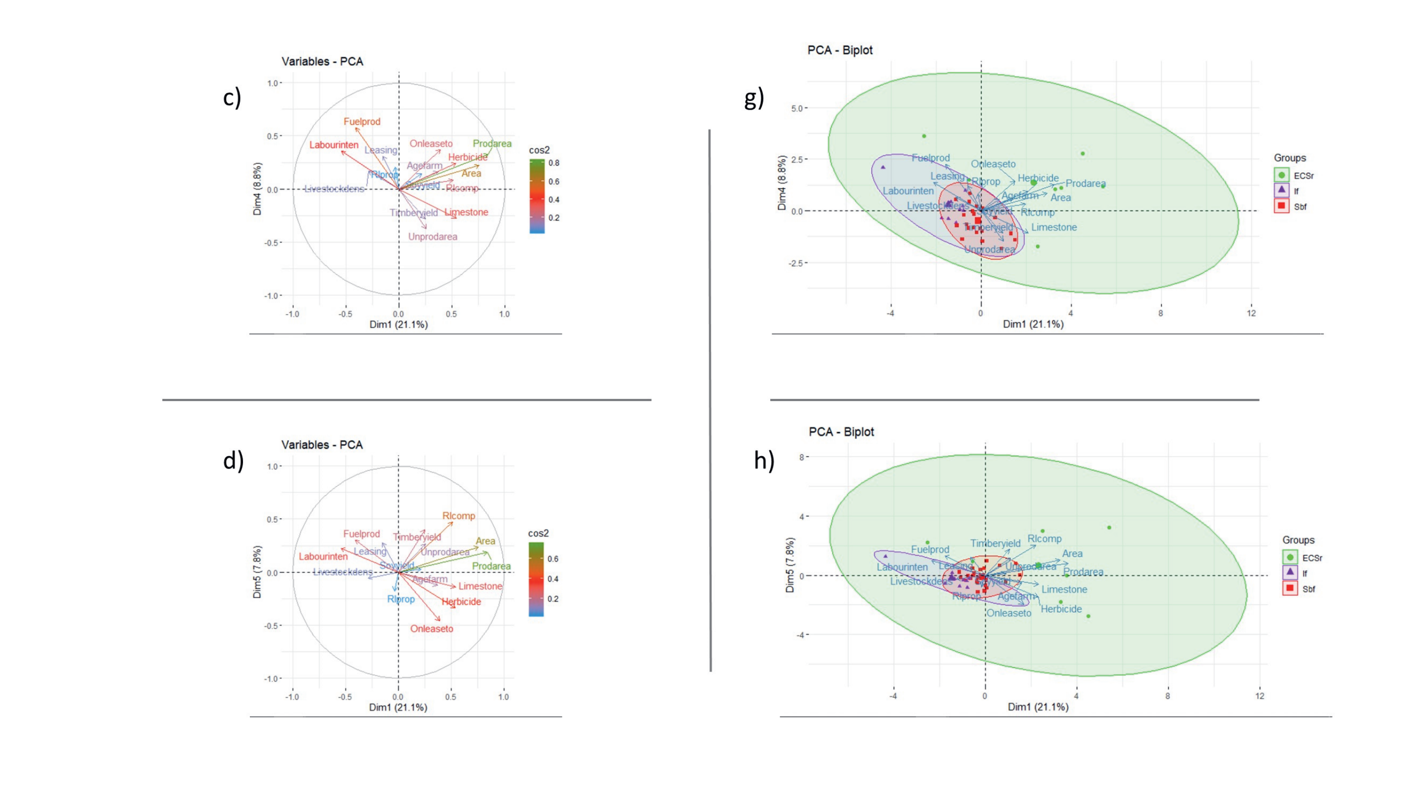


Figure 3.1 Plots of principal component analysis of structural variables from 40 medium and large farms in Paragominas. Panels on the left show (a) PC1-PC2, (b) PC1-PC3, (c) PC1-PC4 and (d) PC1-PC5. Directions of arrows within the circles indicate the strength of the correlation between variables and colors and direction indicate correlation between variables and PCs (i.e., green, high correlation >0.60, blue low correlation <0.2). Right column: PCA biplots for farm types (Extensive cattle-soybean ranches (ECSr), Integrated farms (If) and Soybean-based farms (Sbf) for PC1-PC2 (e), PC1-PC3 (f), PC1-PC4 (g) and PC1-PC5 (h).

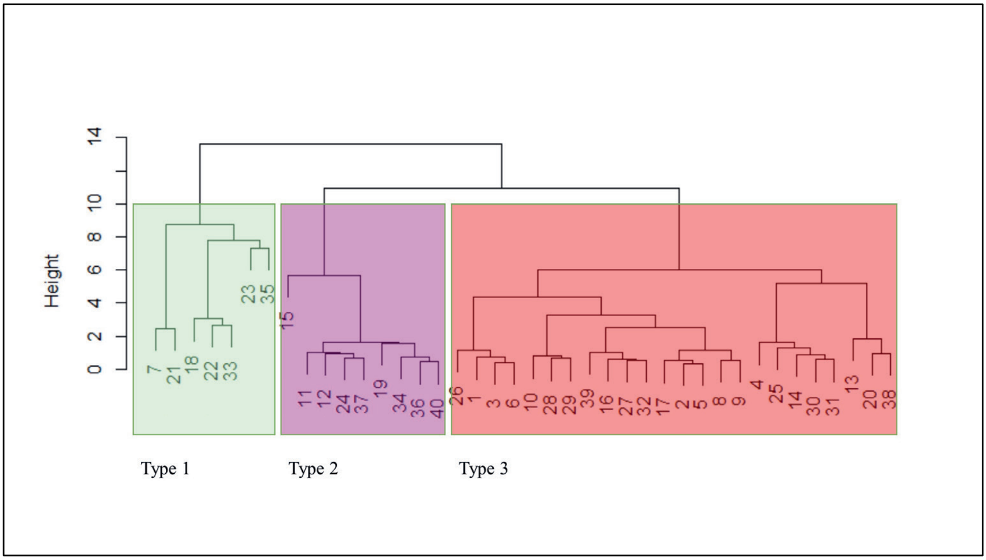


Figure 3.2 Cluster dendrogram for 40 medium and large farms in Paragominas using Ward's method of cluster analysis. The vertical axis represents the agglomeration coefficients (i.e., height or distance between merged clusters), and numbers on horizontal axis indicate the farms.

3.3.3 Characterization of farm types

3.3.3.1 Farm type 1: Extensive cattle-soybean ranches (Type 1; n=7)

These farms have the largest area with an average size of 11,431 ± 6,942 ha, a relatively low cattle density (0.54 ± 0.43 heads/ha) and relatively low average soybean yields (3,384 ± 296 kg/ha; Table 3.3, Figure 3.3). These are the oldest farms in Paragominas with an average age of 19 ± 13.8 years. These farms represent the traditional model of extensive cattle ranching that began as a strategy for land appropriation during the colonization phase. However, in the last 15-20 years, some of these farms have gradually converted suitable areas towards soybean production. This transition towards grain production is, however, not the case for all the farms in this cluster as two farms are still focusing solely on extensive cattle production. Extensive cattle-soybean ranches tend to be run by local agribusiness firms with sufficient resource endowment to develop and maintain their own road infrastructure to connect to the paved road for transporting their produce (Figure 3.4). As part of their agribusiness portfolio some of these farms also offer agronomic services, such as grain storage in silos, land levelling and contouring, transportation, and vending of agricultural inputs.

3.3.3.2 Farm type 2: Integrated farms (Type 2; n=9)

Farms in this cluster are on average smaller (1,245 ± 1,330 ha) than the Extensive cattle-soybean ranches but have a higher livestock density (1.86 ± 0.91 heads/ha; Table 3.3; Figure 3.3). This cluster comprises different types of integrated farming systems. For example, there are three cases of the "Barreirão" agro-pastoral system, which is designed to recover degraded pastures through the integration of forages (e.g., *Andropogon gayanus*, *Panicum* spp.) with crops, such as sorghum, maize, and soybean every 3-4 years. One farm of this cluster adopts the "Santa Fé" system, which consists of a continuous integration of maize and pastures. The grazing cattle density is higher in the Santa Fé system than in the Barreirão system to prevent pastures from seeding during the dry season but leaving enough residual biomass for the next planting season. In this group of farms there is also a case of a silvo-pastoral system in which trees and livestock are integrated through the establishment of forest patches across pastures using native (e.g., *Joannesia princeps*, *Tabebuia serratifolia*, *Swietenia macrophylla*) and exotic (e.g., *Eucalyptus* spp. and *Acacia* spp.) tree species. The forest patches are considered important for livestock by the farmer because they provide shade and shelter from insects that may transmit diseases or cause animal discomfort. A fourth form of integration in this cluster is an agroforestry system with cocoa (*Theobroma cacao*) in association with mahogany (*Swietenia macrophylla*) and teak (*Tectona grandis*).

While most Integrated farms are smaller than the Extensive cattle-soybean ranches, some of the Integrated farms are owned by large agribusiness firms from other regions of Brazil. Integrated farms are well resource endowed as some of these agribusiness firms own several farms in and outside Paragominas. In one case, the manager referred to investments outside the agricultural sector, such as restaurant chains. High levels resource endowment on these farms is also reflected by the high capital and knowledge intensity that integrated systems demand as they typically require specific technologies, agricultural inputs, and qualified labor.

3.3.3.3 Farm type 3: Soybean-based farms (n=24)

Farms in this cluster have an average size of 1,646 ± 1,197 ha and are the youngest farms (11 ± 6 years) with the lowest average proportion of Legal Reserve (32 ± 29%). Soybean-based farms have an average soybean yield of 3,262 ± 361 kg/ha and the smallest livestock density (0.39 ± 0.29 heads/ha) (Table 3.3, Figure 3.3). A sub-group of this cluster (n=8) is formed by relatively small farms that were established after subdividing large farms 10-15 years ago to allow land access for new settlers (Figure 3.2). The small Soybean-based farms are run by individual farmers, operating on 5-10 years leasing contracts. In some cases, these farmers also lease forested areas to compensate for the absence of Legal Reserves in their farms. Small Soybean-based farms have enough investment capacity to purchase machinery and agricultural inputs but rely on cooperatives and associations to sell and transport their production. These small farms tend to be near the urban center where the first intensification transitions towards grain production started 20 years ago.

The second sub-group in this cluster are large Soybean-based farms (n=16) with large Legal Reserves and located in areas more than two hours' drive away from the road (Figure 3.2). These farms can intensify grain production despite the remoteness to the paved road due to high resource endowment, allowing access to machinery to fix unpaved roads, planes for transportation, and silos for storing grains (Figure 3.4). These farms are run by local agribusiness groups that have the financial capital to intensify soybean production despite the logistical challenges of their location. Large Soybean-based farms have a similar history of cattle ranching like the Extensive cattle-soybean ranches, but they are increasingly specializing in grain production.

Table 3.3 Main farm structural variables and landscape composition of three farm types based on a sample of 40 medium and large farms in Paragominas.

Farm type	Agricultural intensification process and forest cover	Farm area (ha)	Legal Reserve (proportion % of total farm size)	Farm age (years)	Soybean yield (kg/ha)	Cattle density (heads/ha)
1. Extensive cattle-soybean ranches	Extensive cattle ranches converting towards grain production in fertile areas (i.e., clayey plateaus). Presence of large Legal Reserves with variable levels of forest degradation.	11,431 ± 6,942	0.45 ± 0.24	19 ± 13.8	3,384 ± 296	0.54 ± 0.43
2. Integrated farms	Farms heading towards integrated agricultural systems. Presence of large Legal Reserves with variable levels of forest degradation.	1,245 ± 1,330	0.47 ± 0.05	16 ±11.3	3,150 ± 212	1.86 ± 0.91
3. Soybean-based farms	Farms oriented towards intensive soybean monoculture. The small farms produce soybean near the urban center and lease Legal Reserves outside the farm. The large farms produce soybean monocultures in remote areas and have Legal Reserves with low levels of forest degradation.	1,646 ± 1,197	0.32 ± 0.29	11 ± 5.9	3,262 ±361	0.39 ± 0.29

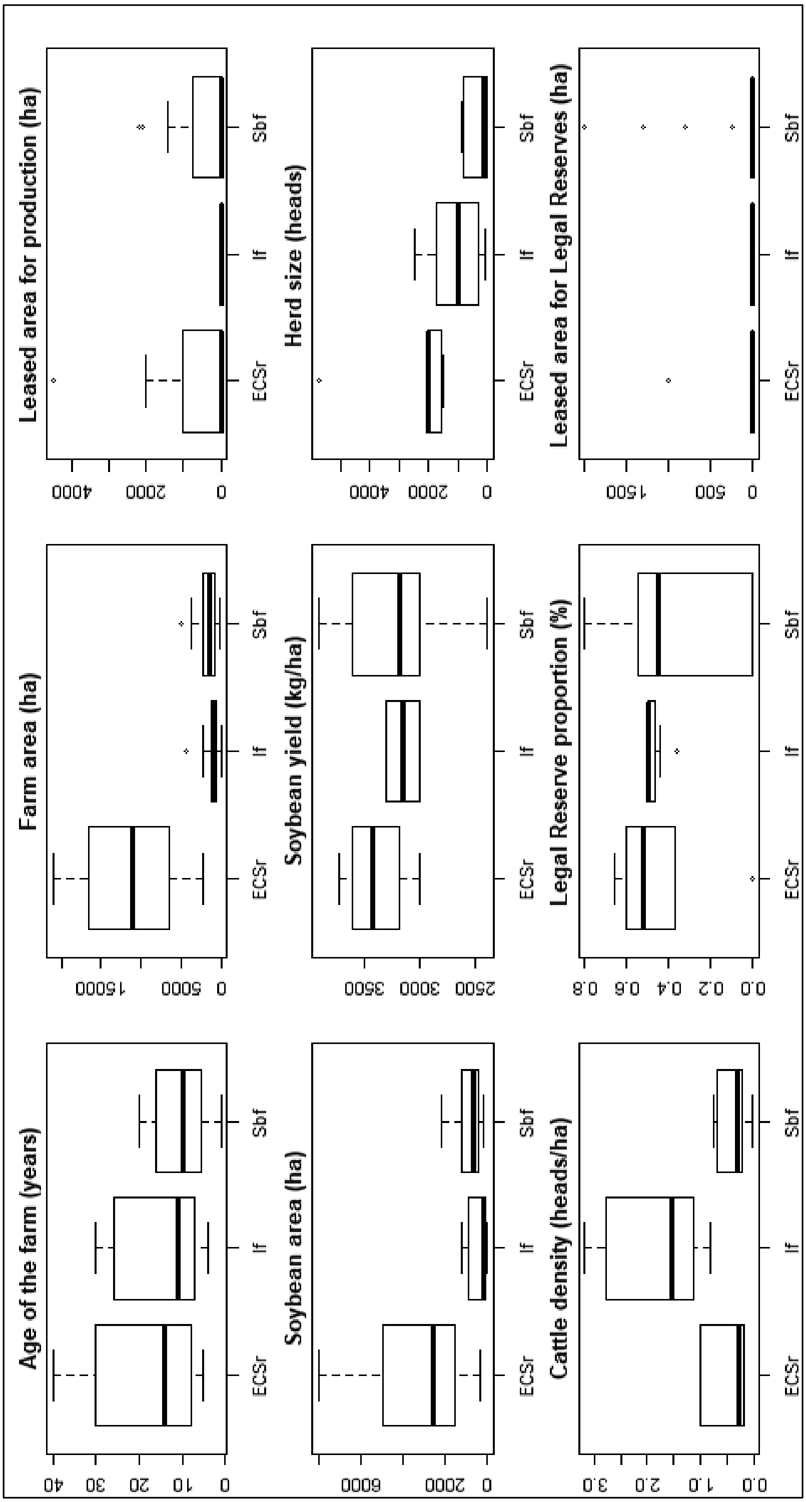


Figure 3.3 Box plots of key variables for Extensive cattle-soybean ranches (ECSr; Type 1), Integrated farms (If; Type 2) and Soybean-based farms (Sbf; Type 3) in Paragominas.

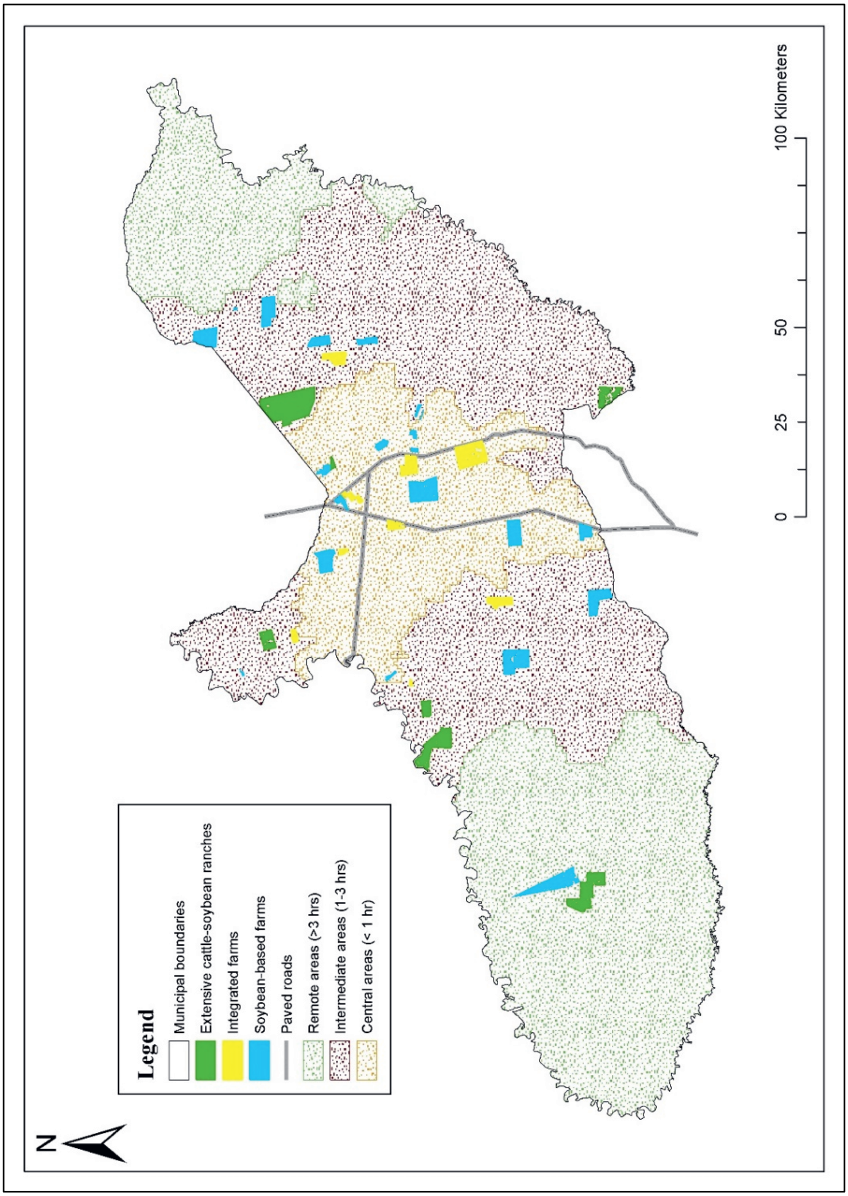


Figure 3.4 Distribution of surveyed farms in Paragominas in relation to distance and traveling-time to paved road (Carvalho et al., 2019).

3.4 Discussion

We conducted a farm typology to assess the diversity of farms and the related processes of agricultural intensification in the municipality of Paragominas in the eastern Amazon region. Our farm typology indicated that the current agricultural intensification scheme in Paragominas centers around agro-industrial practices to produce soybean and meat. Furthermore, our results suggest a range of agricultural intensification in which the traditional extensive agricultural model is gearing towards more intensified systems. This intensification entails the conversion of pastureland to arable fields on mechanizable, fertile soils to produce soybean. Our typology indicated three main farm types: Extensive cattle-soybean ranches, Soybean-based farms, and Integrated farms.

Resource endowment (i.e., PC1) was one of the main determinants for agricultural intensification as it related to area size, productivity, land security, labor intensity and age of the farm (Figure 3.1a). The latter was a key discriminatory variable as the youngest farms tended to be the smallest farms that emerged as a result of land partitioning and are highly specialized on intensive soybean production without the preservation of Legal Reserves within the farm boundaries. In relation to this, other distinguishing variables for Soybean-based farms were whether farms lease areas for forest conservation outside the farms (i.e., Legal Reserves compensation) or lease land for production (Figure 3.1e). Livestock density and labor intensity were also discriminatory variables particularly for Integrated farms. This farm typology may be useful to identify possibilities and needs per farm type for envisioning possible alternatives beyond agro-industrial practices towards ecological intensification schemes.

3.4.1 Diversification as an agricultural intensification strategy in Paragominas

Our results suggest that more diversified farms (e.g., Integrated farms) are run by affluent agribusiness firms with access to specialized labor and inputs. Studies conducted in the western Amazon region, however, suggest that farm diversification typically emerges among smallholder farmers as a consequence of small property size in order to minimize the risk associated with the yield of a specific crop (Walker et al., 2002; Bell, 2011). A large farm area size, nevertheless, may also prompt diversification as there is more farm area to spare (Benin et al., 2004; Bravo-Ureta et al., 2006; Chavez et al., 2010). In the state of Rondônia, for instance, establishing agroforestry systems required higher resource endowment and labor availability as compared to other production systems (Perz, 2005). Thus, farm size and financial capital may enable farm diversification in the region, if supported by the farmers' ultimate objectives.

Land use composition within a farm can facilitate or obstruct the diversification of agricultural production in the region. For example, cattle ranches in the western Amazon region specializing in livestock production were found to diversify less as compared to other farms in the region (Caviglia-Harris and Sills, 2005). This aligns with our findings regarding the Extensive cattle-soybean ranches in Paragominas where extensive cattle ranching continues to be the prevailing farming system. This can be partially explained by the fact that cattle ownership is perceived as a store of wealth in agricultural frontiers (Caviglia-Harris and Sills, 2005). Cattle ranching in the western Amazon region was associated with the oldest and largest farms (Perz, 2005; Bell, 2011), consistent with our own typology. Therefore, barriers for diversification in Paragominas can be partly linked to cultural and identity aspects that in turn relate to the age of the farm and the societal and economic dynamics of cattle production that emerged since the colonization phase. In Paragominas, this means that traditional cattle ranches may be less predisposed to diversify due to cultural and social reasons.

Some studies suggest a positive relationship between land ownership and diversification as farmers are reluctant to invest on leased land (Caballero, 2001; Bravo-Ureta et al., 2006). In our study this trend was observed on the small Soybean-based farms operating on rented lands. One of the main concerns of these farmers was the limited duration of the contract agreements, whilst long-term investments are required to make soybean production financially viable, such as the purchase of farm machinery. Therefore, diversifying agricultural production under land leasing conditions appears problematic because the return on investment in diversified systems may take place after the foreseeable lease contract, discouraging farmers to invest in these practices.

The geographical agglomeration of soybean supply chain actors in Paragominas may also deter prospects of agricultural diversification. The concept of agglomeration economies (Garrett et al., 2013) postulates that besides biophysical characteristics and transportation, farm production orientation also depends on the spatial concentration and diversity of supply chain actors in a particular region. In our study area, the concentration of Soybean-based farms near the urban center exemplifies this agglomeration effect as particularly the smallest Soybean-based farms benefit from positive economic externalities derived from its geographical location (e.g., access to cooperatives, credit banks, and agricultural inputs). This agglomeration effect among farms and agribusiness firms may be a factor reducing the possibilities to implement alternative productive systems in Paragominas. The positive externalities associated with agglomeration economies may be less important for farms with more resource availability allowing them to act independently from other farms and businesses in proximity. In this respect, Extensive cattle-soybean farms and Integrated farms seem a priori better positioned to diversify agricultural production than Soybean-based farms.

Access to broader social networks can be an opportunity to introduce diversification. For instance, membership to local associations and farmer groups can facilitate widespread adoption of novel practices and novel farming systems, such as agroforestry (Godtland et al., 2004; Sills and Caviglia-Harris, 2015). This phenomenon has been documented in the Cerrado region where the development of the agribusiness sector in the last 20 years has been shaped by spatially concentrated social networks (de Sowa and Busch, 1998). Thus, farm area, resource endowment, farm composition, land tenure and agglomeration effects are all factors that can influence the possibilities for agricultural diversification beyond the current agro-industrial model in Paragominas. Policy mechanisms (e.g., Payment for Ecosystem Services, Clean Development Mechanisms) are, however, needed to gear the direction towards more diversified and sustainable production models in the region based on tree-like systems, such as agroforestry and integrated crop–livestock–forestry systems (Alves et al., 2017; Nunes et al., 2020).

Our results show that re-agroforestation (Michon et al., 2000) and forest restoration (Diederichsen et al., 2017) could be pertinent forms of diversification on abandoned pastures and fallows of Extensive cattle-soybean ranches. Integrated farms have made the leap towards integrated systems in which the animal and crop component are put together as a strategy to recuperate pastures and capitalize over mid-term investments (Pereira et al., 2011). In these agropastoral systems, the forestry component could be added by introducing lines of timber, fruit or leguminous trees that can provide food and forage (Russo, 1996; Kremen, 2020). Soybean-based farms may be less diversified farms than integrated systems because most of these farms have leased areas that were specifically selected to produce soybean. This is particularly the case for the smallest Soybean-based farms located close to the urban center and that have limited or none surrounding forests. Agricultural diversification on these farms of soybean monocultures appear unfeasible unless the current system is replaced, however living fences and forest edges could be established in these farms in areas unsuitable for production (e.g., such as the borders of the plateaus formed by a duricrust layer) as a strategy to decrease soil erosion and enhance forest connectivity (Harvey et al., 2004; Harvey et al., 2005). For large Soybean-based farms in remote areas diversification could also take form as agroforestry systems in open unmanaged areas of the farm. Finally, forest conservation is important for farms at further distance from the paved road (mainly Extensive cattle-soybean ranches and large Soybean-based farms) because these regions contain the most undisturbed forests in Paragominas (Barlow et al., 2016; Bourgoin et al., 2018).

3.4.2 Agricultural intensification, land use dynamics and landscape consolidation in Paragominas

Historically, frontier Amazonian landscapes have been shaped by land use changes, deforestation, and extensive agriculture. Consolidated agricultural landscapes, on the other hand, are characterized by land scarcity and high land rents that stimulate agricultural intensification and the stabilization of the agricultural frontier (Barretto et al., 2013). Consolidated landscapes are characteristic of southern and south-eastern Brazil, while frontier regions are typical of central and northern Brazil encompassing the Amazon region. Extensive livestock production is typically linked to frontier landscapes with limited infrastructure, while intensified crop production requires developed infrastructure as well as a set of complex services, typical of consolidated regions (Barretto et al., 2013).

Agricultural intensification, however, does not necessarily lead to a reduction of deforestation, and needs to be accompanied by forest protection measures (Phalan et al., 2011a; Thaler, 2017). If large-scale deforestation is kept under control, landscape consolidation may have an important effect on land use spatial arrangements within farms of Paragominas. For instance, intensification strategies by farmers are increasingly taking into account biophysical attributes of the agroecosystem, such as soil texture and slope (Plassin et al., 2017). Our typology is consistent with this observation as Extensive cattle-soybean ranches are implementing soybean monocultures on the fertile clayey plateaus while leaving the sandy soils for pastures or natural regeneration. The same is observed in Soybean-based farms, as they are exclusively located on the flat clayey plateaus where mechanization is possible. These land use dynamics suggests a gradual reorganization of the landscape in which clayey plateaus are preferentially used for agriculture intensification over the sandy valleys, in contrast to the cattle ranching expansion phase prior to early 2000s, when sandy valleys were more desirable due to access to water for cattle. This has two possible contrasting implications for forest cover in Paragominas, 1) an increased pressure on the remaining primary forests on the clayey plateaus because these are suitable areas for soybean cultivation, and 2) released pressure on secondary forest succession in sandy valleys that are not mechanizable (Poccard-Chapuis et al., in preparation). Understanding these two processes in connection to agricultural intensification at the farm level will be important to prevent further primary forest loss and allow secondary forest succession. For instance, in Extensive cattle-soybean ranches and large Soybean-based farms, which are typically larger landholdings with considerable forest areas, expansion of soybean monocultures into forested clayey plateaus is likely if no forest conservation policy measures are enforced effectively and no diversification alternatives for intensification are developed.

3.4.3 Limitations of the farm typology

The total farm area surveyed in the 40 farms we analyzed encompasses approximately 60,000 hectares in a municipality of almost 2 million hectares with roughly two thousand registered rural properties in the Environmental Rural Registry (CAR). Our typology should be interpreted with caution as there may be farming systems that we did not capture due to the limited size of our farm sample. Nevertheless, the history of forest frontier in Paragominas unfolding across a specific pedo-morphological pattern (i.e., clayey plateaus intermingled with wide sandy valleys), may allow to make generalizations of farming systems across the landscape in relation to size, history, and relative location to the main road. We did not account for smallholders farming systems in the various settlements of the region because we focused on agricultural intensification aiming at the production of agricultural commodities. Diversity of smallholder systems deserves a separate study to understand the intensification and diversification strategies on small farms of the region and its implications for the landscape.

A second limitation of our study emerges from the potential discrepancy between a farming system and a landholding as delimited by the CAR. Our sampling design equated a CAR unit with a farming system for pragmatic reasons. However, a CAR is a property registration system to monitor forest conservation compliance and not a property title as most farms in Paragominas are non-titled lands. Thus, a CAR unit may correspond to a farm, but a farm may also be composed of different CAR units, or one CAR may be composed of several farms. Elucidating all these possibilities during our surveys was not feasible as it involved sensitive privacy issues for farmers. From a conceptual point of view, the delimitation of a farming system can also be problematic when considering, for example, common lands or off-farm income (Giller, 2013). The latter was the case for various of the farms we interviewed with broad investments portfolios outside the agricultural sector. In our study we solved this conundrum by equating a farm to a rural property as defined by the CAR.

3.5 Conclusions

In this paper we identified three different farm types in the municipality of Paragominas in the eastern Amazon region based on structural farm characteristics. Given that the extensive agricultural model deployed during the colonization of the Amazon has been reverted by policy and market induced land constriction, the three farm types we identified suggest a range of agricultural intensification from Extensive cattle-soybean farms to Soybean-based farms and Integrated farms. This process of agricultural intensification has been steered by an agro-industrial production model under a low-deforestation context. Yet, it is not clear whether deforestation will remain under control in the mid and long term, as recent spikes of deforestation have been detected in the region during the last five years. In a non-zero deforestation context, the current agricultural intensification in the form of soybean monocultures will probably lead to agricultural expansion into forest areas, contrary to the logic of landscape consolidation and the land sparing paradigm. Moreover, a redesign of large-scale industrial farms following ecological intensification principles may reduce trade-offs between production and forest and biodiversity conservation. For this reason, implementing agricultural diversification measures as an intensification strategy in already open areas to restore soils and forest coverage can be critical to enable synergies and multifunctional landscapes. Our farm typology can be a tool to identify diversification pathways that incorporate more diversified productive systems such as agroforestry and other integrated systems that enhance tree coverage in the landscape. Further research is needed to tailor specific strategies for each one of the farm types we identified to assess the ecological and agronomical implications of implementing such pathways. Ultimately, this can lead to generating farm management plans and protocols based on ecological intensification principles that consider both farm structural characteristics and biophysical characteristics of the surrounding landscape.

3.6 Acknowledgements

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Chapter 4

Landholders' perceptions on Legal Reserves and agricultural intensification: diversity and implications for forest conservation in the eastern Brazilian Amazon

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Under review

Abstract

Forest conservation on privately owned lands is a cornerstone of the Brazilian environmental policy framework. Brazilian legislation requires that all farms in the country maintain and protect forest areas known as Legal Reserves. While this has major implications for forest conservation and agricultural production, its implementation requires that we understand landholders' perceptions towards Legal Reserves. We applied Q methodology to identify different perspectives of medium and large landholders on Legal Reserves and their relation to agricultural intensification in the municipality of Paragominas, eastern Amazon. We conducted 31 interviews in which landholders sorted 36 statements in a quasi-normal distribution array. Three groups of landholders were identified: 1) Agribusiness-conservation coexistence enthusiasts (n=18) were interested to explore alternative landscape designs and legislation that may deliver better conservation and production outcomes; 2) Policy complacent-market responders (n=7) showed no interest in Legal Reserves reforms and were the most market driven group; 3) Conservation-development antagonists (n=4) held the most critical views against Legal Reserves and perceived these as an obstacle for their production goals. While Paragominas has achieved notable successes in halting large-scale deforestation through a social "Green Municipality" pact, addressing persisting forest degradation and fragmentation in the region remains a key priority. Local governance initiatives that account for multi-stakeholder perceptions on forest conservation can foster dialogue and mutual understanding to effectively conserve and restore Legal Reserves. Insights on large landholders' perceptions on Legal Reserves can inform such governance processes to reconcile forest conservation and sustainable agricultural intensification in Paragominas.

Keywords: Legal Reserve, farmer perceptions, forest conservation, agricultural intensification, Q methodology, Brazilian Amazon

4.1 Introduction

Reconciling agricultural production and forest conservation is a major challenge in many parts of the world. In tropical countries, deforestation is often linked to the expansion of croplands and pastures as global demands for agricultural commodities keep increasing (Angelsen, 2010; Henders et al., 2018). In the Amazon region of Brazil, the development of agriculture has been linked to deforestation since its colonization in the 1960s; currently roughly 40% of the country's total cattle population and soybean monocultures are located in the Amazon biome (Koch et al., 2019). In the last forty years, the Brazilian Amazon forest has lost 20% of its area (da Cruz et al., 2020) despite the fact that policies requiring forest conservation on private farms date back almost ninety years. As a result, stricter policy measures were put in place since the beginning of the 2000s, such as the expansion of protected areas and the enforcement of command-and-control measures on rural landholdings resulting in an 80% drop-in deforestation rates between 2004 and 2014 (Soares-Filho et al., 2010; Börner et al., 2015; PRODES, 2017).

The most important piece of conservation legislation on private lands in Brazil is the so-called Legal Reserves (LRs) which requires landowners to maintain a fixed amount of area as native vegetation within their properties to protect biodiversity, varying from 80% in the Amazon, to 35% in transition zones between the Amazon and Cerrado, and 20% in the Cerrado, Atlantic forest, Caatinga, Pantanal and Pampa biomes. The legal concept of LRs is unique to Brazil and it is also the most controversial piece of environmental legislation because it limits agricultural activities within rural landholdings without apparent compensation (Santos, 2004). Legislation, however, does allow forest logging for commercial purposes within LRs under an approved management plan[4] including the introduction of exotic species (inciso I-III do Artigo 22, Lei 12.651/2012). Currently, LRs cover one third of the area of Brazil, thereby surpassing the public preservation areas and national parks that cover roughly 20% of the country (Sparovek et al., 2010).

At the same time, efforts to link compliance of LRs with trade of agricultural commodities through value chain interventions have recently emerged in the Amazon. These include most notably a soybean moratorium which was the first voluntary zero-deforestation agreement in the region where soybean traders committed to avoid soybean coming from deforested lands

[4] LRs in the Amazon are allowed to extract up to 30 m^3 in logs/ha with cycles of 35 years, and 10 m^3 in logs/ha with cycles of 10 years (Brancalion et al., 2012). Despite being allowed by legislation under a management plan, the actual sustainability of these have been put into question, c.f., Fearnside, 2017b.

after July 2006 (Gibbs et al., 2015). Other examples include the Federal Public Prosecutor's Offices (Ministério Público Federal, or MPF) TAC agreement (Terms of Adjustment of Conduct) and the G4 agreement, both signed in 2009, where meatpacking companies committed to block trade with ranches with illegal deforestation (G4 agreement prohibits any forest clearing) or unregistered in the Environmental Rural Registry (CAR) (Gibbs et al., 2016).

Simultaneously, frequent modifications and political disputes around LRs, have caused confusion and juridical uncertainty in its application and hampered its effective adoption (Mueller, 2018; da Fonseca, 2019). Furthermore, even if effectively implemented, there is a need for policy tools that go beyond the mere maintenance of forest cover that take into account aspects such as forest disturbance (e.g., selective logging and forest fires) and habitat fragmentation (Barlow et al., 2016). This convoluted land governance context has far reaching implications for forest and biodiversity conservation and for land management. While landholders are in charge of operationalizing the concept of LR, they are at the same time its major critics (related to e.g., financial burden, obstacle for infrastructure, liability for fires). Historically, this is not surprising, as landownership has always been a contentious issue in the Brazilian Amazon: the occupation and distribution of lands have historically been characterized by violence and conflicts between different social actors (Simmons et al., 2002; Simmons, 2005). The exercise of private property in this region thus, has to be understood in the context of tension between wealth acquisition through the exploitation of natural resources and forest conservation (da Fonseca, 2019). Therefore, understanding landholders' perspectives on LR is fundamental for any prospect of environmental governance that aims at forest and biodiversity conservation in this agricultural commodity frontier of the eastern Amazon region.

Here we assess landholders' perceptions towards LRs in an agricultural commodity frontier in northeastern Pará State, Brazil, to further understand if LRs and agricultural intensification are perceived as antagonistic, synergistic, or if more nuanced views exist that may help to elucidate entry points for enhanced implementation and compliance. We define perception as an individual's interpretation of external stimuli based on prior experiences which closely relates to "attitude" as a predisposition to behave in a particular way (Pickens, 2005; Lindsay and Norman, 2013). To assess these perceptions, we applied Q methodology, a method developed in the field of psychology to understand individuals' subjective viewpoints based on quantitative and qualitative data (Stephenson, 1935; Brown, 1993; 1996). This methodology has been used in the Amazon region to study perspectives on agricultural technologies (Pereira et al., 2016), REDD+ (Schneider et al., 2015), forest fires (Cammelli et al., 2019), and jaguar (*Panthera onca*) conservation (Bredin et al., 2018).

4.2 Historical and political background of Legal Reserves

The first attempt to protect forests on private lands in the Brazilian Amazon dates back to the first Forest Code from 1934 (Lei Federal no.23.793/34) that stipulated no landowner could clear more than 75% of the forest within the property limits (da Fonseca, 2019). Later in 1965, a new Forest Code (Lei Federal no.4.771/65) was issued prohibiting forest exploitation in the absence of an authorized management plan as well as clear cuts beyond 50% of the property area (da Fonseca, 2019). The 1965 Forest Code defined LR as a forest area inside rural properties necessary for the sustainable use of natural resources, the conservation and rehabilitation of ecological processes, and the conservation of biodiversity. It also defined the location and dimensions of Areas of Permanent Protection[5] (APPs) for the conservation of riparian forests, springs and slopes (Brasil, 1965). In 1989, federal law (Lei Federal no. 7.803) introduced the obligation for rural landowners to register LRs in the official Property Registry (Registros de Imóveis), establishing a formal mechanism to prove the maintenance of LRs (Brasil, 1989; Santos, 2004; Castro, 2013). This signified a radical change for landholders from the 1970-1980 period when government investments, tax incentives and subsidized credits for large cattle ranching were major drivers for colonization and deforestation of the Amazon (Fearnside, 2005).

In 2012, the Native Vegetation Protection Law (NVPL) (Lei no. 12.651) replaced the 1965 Forest Code with important implications for LRs and APPs (Brancalion et al., 2016). Even though this legislation aimed to preserve biodiversity and contain the expansion of agriculture into native vegetation, several subsequent modifications compromised forest conservation. For instance, there was an amnesty for 37 M ha of illegal deforestation that under previous regulations was subject to forest restoration (Guidotti et al., 2017). Furthermore, buffer areas for APPs along rivers were reduced from 30-500 m to 5-100 m (Kröger, 2017), which implied that 5.7 M ha of riparian forest could remain deforested in the state of Pará alone (Nunes et al.,

[5] The definition of the APP is related to geomorphology and the transition between aquatic and terrestrial systems of ecological fragility both in urban and rural areas. LRs are meant for the conservation of natural vegetation specifically in rural properties and can be economically exploited under a sustainable management plan (Pereira et al., 2017). LRs and APPs also differ from Environmental Protection Areas (Área de Proteção Ambiental, APAs), which are one category of federal conservation units both in public or private lands that allow human occupation as they tend to cover large areas such as a basin (Olavo Leite, 2015).

2019). Another amendment included a forest trading mechanism that allowed landholders who deforested more than was legally allowed before 2008 to buy Environmental Reserve Quotas (CRA) to compensate for forest deficits. Legislation (Decreto Nº 9.640/2018) established that CRA can be issued on forest surpluses of existing LRs when forest cover proportions are higher than those defined by the state's Ecological-Economic Zoning plan (EEZ) (see below) (Brasil, 2018). The NVPL also advanced new control measures including the Environmental Rural Registry (CAR), which provides a digital framework to monitor LRs, and the Rural Environmental License (LAR), which regulates activities within the farms, CRA trade, and access to rural credits.

In 2019, however, influential senators pushed for a law amendment (Projeto de Lei. 2362/19) aiming at eliminating LRs altogether. Its supporters argued that LRs impede the development of the agribusiness sector and violate property rights. Eliminating LRs would mean that 167 M ha could be legally deforested in Brazil (Metzger et al., 2019). The proposal was challenged by sectors of society as well as by national research and conservationist institutions, and after an open letter signed by more than a hundred Brazilian scientists was issued, the proposal was dropped (Globo Rural, 2019).

The relaxation of provisions in the new forest legislation in 2012, and the 2019 attempt to dismantle LRs, exemplify how factions of the economic and political sectors have historically framed the forest as idle lands impeding Brazil's modernization (Fearnside, 2008; Kröger, 2017; 2019). In contemporary times these actors embody the agribusiness and landowners' caucus (i.e., Ruralista or "ruralist") advancing a political-economic agenda that prioritizes private land ownership as guarantor of resources, generally in opposition to social movements, of which most fiercely, the Landless Workers' Movement (Movimento dos Trabalhadores Rurais Sem Terra, MST) (de Mendonça, 1997; Lima, 2016). For the Ruralista, the agribusiness sector and the production of export commodities, provide both an economic engine and vision for the development of rural Brazil (Lima, 2016). In this paper we investigate perceptions towards LR and agricultural intensification from medium and large landholders because these are stakeholders that *a priori* ascribe to the Ruralista vision of development in the Brazilian Amazon, and because they possess most of the land and consequently most of the forest under a LR requirement in the region. Elucidating their views on LR therefore, can provide pathways for consensus towards effective forest conservation in the eastern Amazon.

4.3 Methods

4.3.1 Study area

Our study was carried out in the northeastern region of Pará State in the municipality of Paragominas (19,342 km^2). The municipality was founded in 1965 in proximity to the federal road BR-010 that connects to the capital Brasilia (Veríssimo et al., 1992). For six decades, this region was exposed to land degradation and deforestation due to the activities of pioneers who originated from other regions of the country and opened and expanded the agricultural frontier (Poccard-Chapuis et al., 2014). These activities initially consisted of extensive cattle ranching, followed by intense logging during the 1980s until late 1990s, and diversified into eucalyptus plantations and soybean monocultures since the early 2000s (Veríssimo et al., 2002; Piketty et al., 2015).

In 2008, the municipality was blacklisted by the Federal Government as one of the highest deforester municipalities in the region. This brought the imposition of punitive measures (i.e., land embargos, credit restrictions and fines for illegal activities) conditioned to reducing deforestation under 40 km^2/year, deforestation rates below 60% of the average rate from the past two years, and having 80% of the territory registered in the CAR (Piketty et al., 2015). In response, a social pact formed by the rural elite and the municipal government launched the Green Municipality initiative to end large-scale deforestation and register each rural property in the CAR (Viana et al., 2016).

The required proportion of LRs in Paragominas can vary for each landholding as the NVPL allows a resizing from 80 to 50% of the total farm when a state has an approved EEZ plan developed by the state's Environmental Secretary, and at least 65% of the state is covered by national parks or public conservation units. Therefore, Pará State legislation (Lei Stadual no.7.243/2009) allows the reduction of LRs to 50% for farms inside consolidation zones (i.e., areas delimited by the EEZ that were deforested up to July 2008) that acquired forest liability before May 2005. According to the CAR database (http://www.car.gov.br/publico/imoveis/index), 53% of the 2,259 registered landholdings in Paragominas comply with the LR and APP requirements (covering 1 M ha), 44% of the registered landholdings are pending approval due to some anomaly (covering 0.84 M ha), and 3% (63,000 ha) have had its approval cancelled due to misinformation or infractions. Paragominas nevertheless, has a positive balance of LR of 0.36 Mha (i.e., surplus minus deficit) (Nunes et al., 2016), although roughly half of its APPs are deforested (Nunes et al., 2014).

Despite being an old forest frontier, Paragominas still conserves more than half of its territory covered by forest (Table 4.1). Moreover, since large-scale deforestation in Paragominas has been under control since 2010 (Brandão et al., 2020), it may be considered a consolidated frontier with relatively high land prices. This, in addition to access to national and international markets of commodities through the federal highway BR-010 (Pinillos et al., 2020), implies higher opportunity costs for LRs in Paragominas than in other municipalities of the region. Therefore, studying the perceptions of LR in Paragominas is representative of similar consolidated Amazon frontiers and may provide anticipatory insights for other less advanced frontiers in the region.

Table 4.1 Land use and land cover classes and area size for Paragominas in 2019.

Land use/land cover category	ha	%
Forest*	1,313,816	67.9%
Agriculture**	130,837	6.8%
Pasture	477,009	24.7%
Mining	2,936	0.2%
Urban infrastructure	2,704	0.1%
Water bodies	6,918	0.4%
Total	**1,934,220**	100%

* Approximately 26% corresponds to secondary forest (340,000ha) and 1% to forest plantations (13,300 ha) (Piketty et al., 2015). The rest corresponds to primary forest with different degrees of forest degradation due to fire, selective logging, or both (Martins et al., 2013; Berenguer et al., 2014; Bourgoin et al., 2018). ** 84% of agriculture is under soybean cultivation (110,173 ha). Data source: Mapbiomas (https://mapbiomas.org/estatisticas).

4.3.2 Q methodology

Q methodology is a method originating in the field of psychology to study people's subjectivity to explore individual’s viewpoints on an issue and to cluster respondents into groups (Brown, 1993). Q methodology can help to describe a population of ideas in relation to other ideas rather than in isolation. Q methodology is implemented through a statements-sorting exercise where participants receive a deck of cards with printed statements and a board with a fixed sorting distribution (see below). The construction of our statements regarding LR was based on views expressed by landholders during semi-structured interviews that were conducted prior to the sorting-exercise. Clustering of opinions is then based on a factor analysis when similar statements significantly load on the same factor allowing for interpretation and narrative articulation (Brown, 1993; 1996; Ockwell, 2005).

4.3.2.1 Sample selection

Q studies usually follow stratified sampling (Lee, 2017), but given the contemptuous nature of the topic (i.e., LR), we decided to follow a random approach to avoid the sole inclusion of participants presumably open to discuss LRs (e.g., "progressive" landholders). Nor was our objective to generalize our results to the entire population. Accordingly, we aimed for our sample to include sufficient diversity of landholders to allow for contrasting patterns of perceptions on LR. Thus, selection of participants was based on a random sample that we generated by associating random numbers to the online CAR database with properties larger than 300 ha. We selected properties larger than 300 ha as this landholder population represents medium and large-scale landholders, so-called "fazendeiros", who hold by far most of the land in Paragominas and excludes smallholder family farmers (average size 25 ha), who hold less land[6].

4.3.2.2 Semi-structure interviews for statement formulation

During the first phase of our fieldwork in March 2018, we conducted 31 farm surveys on farm structural characteristics followed by semi-structured interviews that we initiated by asking landholders two questions: 1) what requirements are needed for the intensification of your farm and increase production? And 2) how do you perceive the requirement of LR in the region? The reason for asking these two questions in this specific order was first, that by starting the conversation focusing on agricultural intensification, we were able to ease the way for discussing the likely uncomfortable topic of LR in a more nuanced way. The second reason is that we aimed at understanding perceptions towards LR in connection to agricultural intensification, i.e., do landholders perceive these as synergistic, antagonistic, or other. We did not provide landholders with a specific definition of agricultural intensification as we sought to capture landholders' own ideas and definitions.

The semi-structured interviews entailed a 60-90-minute conversation with each landholder. After each interview, we assembled the main ideas expressed by the participant into statements regarding LR, agricultural intensification or a combined statement of both topics. This step

[6] Paragominas is a municipality with one of the highest level of land concentration in the region (Simmons, 2004; Sombra et al., 2016). Pará State has a Gini index of 0.68 for land possession (Pinto et al., 2020). The Gini index ranges from 0 to 1 and measures the degree of inequality in the distribution of wealth or land. A Gini index of zero expresses perfect equality (Gastwirth, 1972).

followed a qualitative content analysis approach (Mayring, 2014; Erlingsson and Brysiewicz, 2017) to code and categorize statements into three main categories i.e., “Agricultural intensification”, “Legal Reserve”, and “Legal Reserve and agricultural intensification”. From this analysis a total of 36 statements were selected as the final pool of statements (i.e., Q-concourse) to avoid overlap and maintain representativeness of opinions expressed during the semi-structured interviews (Table 4.2).

Table 4.2 Categories of statements: agricultural intensification (AI), Legal Reserve (LR) or combined statements (LR-AI).

Category of statement	No of statement in Q-sort	Statement
AI	**11**	The performance of the municipality concerning the maintenance of roads and bridges is adequate enough for landholders to invest in agricultural intensification.
n=17	**12**	The duration of land leasing agreements should be defined according to the minimum time that is necessary to consolidate production areas and ensure its viability.
	13	The current local, economic, and political context is favorable for investments that allow industrialization and adding value to the products originating in the agribusiness sector of Paragominas.
	14	Lack of secure land tenure through property titles to access credits is the main barrier for a landholder in Paragominas to increase production and efficiency.
	15	Precision agriculture and silvo-pastoral systems are fundamental technologies for an efficient intensification that should be more applied in Paragominas.
	16	The current research projects developed in the region match landholder's demand for information and data.
	17	Pisciculture is a productive activity that will have a great development in the municipality in the upcoming years and I pretend to invest in this sector.
	18	If the investment capacity of landholders would increase due to credits or government incentives, it would be used mainly for horizontal expansion rather than for vertical integration.
	19	Paragominas does not have comparative advantages in relation to other municipalities of the region.
	20	Currently the work of landholders in the region is valued and has the support of different sectors of society.
	21	The agricultural sector of Paragominas has skilled labor and personnel that meets the demands of agricultural and cattle ranching activities.
	22	There is in the region a cultural aspect of entrepreneurial spirit and agricultural culture that allows the development of the municipality's potential.
	23	The bureaucracy that surrounds the agricultural sector in Paragominas is excessive and affects its productivity and compliance with environmental legislation.
	25	The lack of effective phytosanitary control of machinery and equipment that come into the municipality from other regions is a source of diseases in my property.
	26	The use of agrochemicals is a problem for human health and for the environment but given the absence of alternatives I am forced to use these products.
	27	Some consumers in Brazil want products free of agrochemical products and that demand could change my production system eventually.
	34	It is necessary to produce technology and varieties to grow grains in sandy valleys with the same productivity that in clayey soils.
LR	**1**	The CAR is a useful tool to protect Paragominas' biodiversity and nature in rural properties.
n=6	**4**	The location of LR should be planed to a larger scale than that of a single property taking into account soil conditions and topography to guarantee its positive effect in the whole municipality.

	6	In remote areas LR can be a problematic requirement for a landholder due to the risk of land invasion and extractivism of wood and non-wood resources.
	7	When a landholder needs to compensate areas of LR outside his or her property he or she has knowledge of what happens in the area that is leased.
	32	The current policies and governmental mechanisms are efficient to incentivize compliance with the Environmental Regularization Plan and generate a structural network of connected habitats.
	33	Reforesting valleys, where water springs and rivers pass through is necessary to create biological corridors that allow wildlife safe access to water sources.
LR-AI n=13	2	LR and APP have a positive effect on productivity, since it obliges landholders to be efficient with the land that is already available.
	3	LR is a burden imposed by the federal government that does not know the local context and prevents my property to be profitable according to my expectations.
	5	Some areas of my property could be converted into forest, without that causing an economic loss for me and in order to preserve hydrological resources, soils, and biodiversity.
	8	The money that a landholder stops earning in order to maintain areas of LR is an investment for biodiversity and life quality in Paragominas.
	9	Enrichment planting with fruit trees would be economically interesting if production chains were more consolidated in Paragominas.
	10	The presence of dwellers in proximity to LR of farms do not increase the risk of forest fires in the LR.
	24	In Paragominas there is certainty in relation to the integrity of rural properties, natural resources, material goods, inputs, and infrastructure.
	28	Reforesting sandy valleys in exchange of degraded forests due to fire and logging located in clayed plateaus for agricultural production would be optimizing land use according to soil's properties.
	29	A mechanism to reforest sandy valleys in exchange for areas with degraded forest due to fire and logging in clayey plateaus, would be a negative incentive to clear areas of primary forest.
	30	In areas where the concentration of agricultural land is high, the incidence of pests is less than in areas where agriculture is surrounded by forest and pastures.
	31	Paragominas needs a zoning of the agricultural sector to produce in the most profitable areas and conserve in areas where production is not interesting.
	35	It is important to maintain forest and avoid some agrochemical products to protect bees and pollinators that are important for crop productivity.
	36	The geography of Paragominas is characterized by areas of low economic potential that have high ecological potential for biodiversity, hydrological services, and carbon storage.

4.3.2.3 Q sorting and wrapping-up discussions

The 36 statements were printed on numbered cards to be sorted in a pre-formed, eleven-column, normal distribution pattern (i.e., forced distribution as participants were forced to distribute statements) from "I completely agree (+5)" on the right, through "I feel neutral or indifferent (0)" in the middle, to "I completely disagree (-5)" on the left (Figure 4.1). In May 2018, landowners were revisited, and conducted the card sorting exercise. The reasons for their particular sorting were discussed afterwards and provided an opening to discuss contentious topics that otherwise would have been difficult to approach in a regular semi-structured interview. We report some of these views in the Discussion.

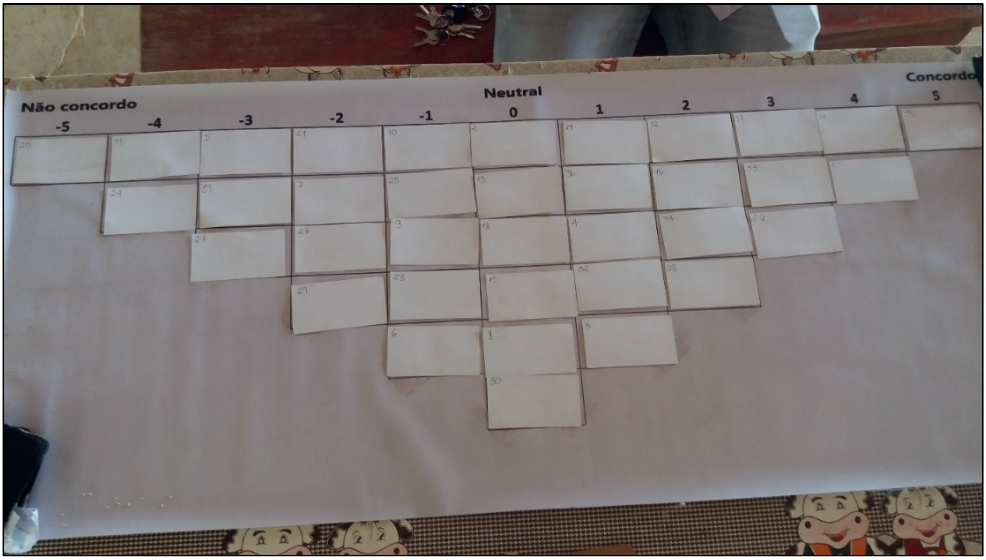

Figure 4.1 Forced normal distribution for the Q-sorting procedure in Paragominas.

4.3.2.4 Factor analysis

The scores of the 31 interviews (i.e., Q-sorts) were arranged in a matrix (36 x 31) with statements as rows, and Q-sorts as columns to perform factor analysis. The number of factors were assessed based on the Latent Root Criterion (i.e., eigenvalues larger than 1), variance explained (at least 40%), number of Q-sorts significantly loading, and feasibility for interpretation (Hair et al., 2006). The factor score array delivered the prototypical sort and indicated distinguishing statements (i.e., statements highlighted in the analysis as significant to the interpretation of a particular factor at a significance level between p = <0.05 to p =< 0.001, see Appendix Table 1) associated with each factor calculated as the weighted average of the Q-sorts. Interpreting the prototypical sort and distinguishing statements allowed articulating the common perspective and narrative of each factor (Kamal and Grodzinska-Jurczak, 2014). Factor analysis was conducted in R 4.1 using the package qmethod (Zabala, 2014).

4.4 Results

We extracted three factors (i.e., viewpoints about LRs) that accounted for 48.3% of the variance (Table 4.3). Factor loads indicated the association of each respondent to factors. From the 31 Q-sorts, 18, 7 and 4 loaded significantly on Factor 1, 2, and 3, respectively. Two sorts did not load significantly for any factor (i.e., unflagged sorts) and were left out of the interpretation (Table 4.4). There were only two consensual statements belonging to the combined category (LR-AI) in connection to the use of agrochemicals, (statement 35, S35), and the geography of Paragominas (S36). On the other hand, there were 14 distinguishing statements particularly from the LR and the LR-AI categories (e.g., S1, S2, S8, S29, S30, S33,) (Table 1 of the Appendix).

Table 4.3 Factors, number of loadings and eigenvalues resulting from factor analysis using three factors.

Factors	n	Eigen values	Explained variance (%)
F1	18.00	8.77	28.28
F2	7.00	3.78	12.20
F3	4.00	2.42	7.80

Table 4.4 Q-factor loadings for each Q-sort performed by the respondents in Paragominas. Bold numbers indicate flagged Q-sorts (i.e., significantly loading for that factor), and "*" indicates unflagged Q-sorts (i.e., sorts not significantly loading to any factor).

Sort number	Factor loadings		
	F1	F2	F3
Q1	-0.037	-0.086	**0.548**
Q2*	0.274	0.226	-0.106
Q3	**0.584**	-0.142	0.352
Q4	**0.706**	-0.122	0.198
Q5	**0.589**	-0.302	-0.002
Q6	**0.685**	-0.052	0.400
Q7	**0.716**	-0.039	0.266
Q8	**0.728**	-0.342	-0.124
Q9	**0.721**	0.075	-0.059
Q10	**0.680**	-0.122	0.041

Q11	**0.672**	-0.181	0.201
Q12	-0.273	**0.913**	-0.072
Q13	0.258	-0.124	**0.719**
Q14	-0.273	**0.913**	-0.072
Q15	**0.545**	-0.243	0.130
Q16*	0.246	-0.171	-0.199
Q17	0.358	**0.398**	-0.006
Q18	0.067	**-0.359**	0.070
Q19	**0.648**	0.268	-0.222
Q20	**0.498**	-0.182	0.072
Q21	-0.273	**0.913**	-0.072
Q22	**0.773**	0.014	0.012
Q23	**0.756**	0.026	0.107
Q24	**0.763**	-0.058	-0.182
Q25	0.371	**-0.433**	0.142
Q26	0.204	**0.398**	0.082
Q27	0.498	-0.118	**0.680**
Q28	**0.545**	-0.083	0.182
Q29	**0.409**	-0.051	-0.026
Q30	0.383	-0.132	**-0.503**
Q31	**0.563**	-0.184	0.429
Explained variance (%)	28	12	8
Significant loaders (n)	18	7	4

4.4.1 Factor 1: Agribusiness-conservation coexistence enthusiasts

Factor 1 accounted for 28% of the variance and represented the largest group with 18 respondents. Landholders in this group were critical of conservation policies and were unique in favoring plans to relocate LRs from areas suitable for agricultural production to less favorable areas due to soil conditions and remoteness (+2; S4; Table 1 in Appendix). They agreed (+3) that Paragominas needs a zoning of the agricultural sector to produce on the most fertile soils and conserve in areas where production is not feasible (S31). They favored (+4) the potential implementation of a land use change mechanism (i.e., “troca de areas” meaning exchanging or swapping areas) that would allow reforestation and restoration of sandy valleys in exchange of clearing degraded forests located on clayey plateaus suitable for crop production (S28). They disagreed (-5) that the municipal government does enough concerning maintenance of infrastructure to incentivize agricultural intensification (S11). The landholders in this group also perceived (+5) the lack of secure land tenure through property titles to access credits as the main barrier for agricultural intensification (S14). Thus, the distinctiveness of these landholders pertains to their view that new land use planning approaches are needed. We refer to these landholders as Agribusiness-conservation coexistence enthusiasts. They are predominantly soybean producers originating from Brazil's southern and south-eastern regions and have landholdings located in the central region of Paragominas. Other more distant landholdings from this group were the largest properties that we encountered (Table 4.5).

4.4.2 Factor 2: Policy complacent-market responders

Factor 2 explained 12% of the variance and represented seven respondents. Landholders in this group showed slight indifference towards potential changes in the landscape and environmental policies. Despite some ambivalence, they appeared complacent with the current environmental legislation. This is reflected in their distinctive opinion (+2) that current policies are efficient to incentivize environmental compliance (S32). Similarly, these landholders agreed (+4) that the presence of land occupants near LRs does not increase the risk of forest fires (S10). They were the only group who perceived (+2) that LRs are an investment for biodiversity and life quality in Paragominas (S8) but disagreed (-5) with the usefulness of CAR as a tool to protect biodiversity (S1). Furthermore, these landholders seemed to disfavor (-2) land use reallocation initiatives (S28), and unlike the other groups, these landholders were inclined towards (+2) investing in horizontal expansion rather than in agricultural intensification (S18). These landholders were also unique against (-3) the timeliness to invest in the agricultural sector (S13). The skepticism of landholders in this group was also reflected in their perception that the region does not have a culture of agricultural entrepreneurship (S22). However, these landholders appeared as the most market-driven by acknowledging (+3) that they could change their production systems if the demand for agrochemical free products increases in the national market (S27). They also perceived (+2) the use of agrochemicals as a problem for their health and for the environment (S26). These landholders were evenly distributed between soybean and livestock producers and they represented the oldest farms suggesting earliest settling in the region (Table 4.5).

4.4.3 Factor 3: Conservation-development antagonists

Factor 3 accounted for 8% of the variance with four respondents. Landholders in this group perceived conservation policies as antagonistic to their production goals. They were the only group that considered (+1) LRs as a burden imposed by the Federal Government (S3) and diverged from the idea that (-3) LRs are an investment for life quality in Paragominas (S8). They also disagreed (-1) with the possibility that LRs may have positive effects on productivity (S2). These landholders were the only group who perceived (+3) pisciculture as an interesting investment opportunity following a lift on the ban to cultivate exotic fishes in the region. Furthermore, they also favored (+3) developing high-yielding crop varieties suitable for sandy valleys (S34) as opposed to the other landholders who were inclined to maintain forest in these areas. These landholders did not acknowledge (-4) the possibility that their production system could eventually change as a response to increasing demand for agrochemical-free products (S27). Similarly, they disagreed (-5) that the use of agrochemicals could cause health and environmental problems (S26). Landholders in this group seemed to adopt a position in which "nature" needs to be "fought back" with technology and labor to accomplish the desired agricultural production and regional economic development. Therefore, we named this group Conservation-development antagonists. These landholders were all soybean producers with the most remote landholdings in the region (Table 4.5).

Table 4.5 General characteristics for each factor concerning agricultural production focus, state of origin, average landholding size, age of farming production system and remoteness.

Factors (landholder group)	**n**	**Production focus and state of origin**		**Average landholding size (ha)**	**Average age of production system (years)**	**Average driving time to Paragominas city (minutes)**
Agribusiness-conservation coexistence enthusiasts	18	Soybean	14	2,937	14	70
		Paraná	5			
		Rio Grande do Sul	4			
		Espírito Santo	2			
		São Paulo	1			
		Maranhão	1			
		Minas Gerais	1			
		Livestock	4			
		Espírito Santo	2			
		Paraná	1			
		Minas Gerais	1			
Policy complacent-market responders	7	Soybean	3	746	23	77
		Paraná	3			
		Livestock	4			
		Minas Gerais	1			
		Rio de Janeiro	1			
		Espírito Santo	1			
		Paraná	1			
Conservation-development antagonists	4	Soybean	4	2,361	15	90
		Espírito Santo	2			
		São Paulo	1			
		Pará	1			

4.5 Discussion

In this study we assessed the perceptions of medium and large landholders on LR and agricultural intensification. We identified three broad groups. Agribusiness-conservation coexistence enthusiasts perceived that forest conservation and agricultural intensification can be integrated by reconfiguring the current landscape. Policy complacent-market responders were less interested in policy changes but appeared the most responsive to market demands and showed concern regarding the risks associated with agrochemicals on human health and the environment. Conservation-development antagonists were the fiercest critics of the current environmental framework claiming that the Federal Government has passed on to them the responsibility to preserve the forest without any compensation in return.

4.5.1 Factors driving landholders' perceptions on Legal Reserves

A prevailing viewpoint, especially among Agribusiness-conservation coexistence enthusiasts and Conservation-development antagonists, was the lack of instruments to incentivize effective implementation of LRs. A study conducted in the state of Mato Grosso reports similar views from landholders who considered environmental federal policies too general to be practical at the local level and affected by corruption in its implementation (Bredin et al., 2018). Similar concerns were expressed in Paragominas, where Agribusiness-conservation coexistence enthusiasts and Conservation-development antagonists stressed the need for reforms to increase local governance and independence from federal regulations. The Agribusiness-conservation coexistence enthusiasts, for example, showed interest in a "troca de areas" or land use exchange mechanism restricted by the current legislation. Conservation-development antagonists went further as to refer to LRs as an imposed burden they would like to eliminate, alluding to the contradiction between past colonization and current environmental policies (Schmidt and McDermott, 2014).

Landholding size, crop diversity and proximity to the urban center can be positively associated with a willingness to preserve LRs in the region (Schneider et al., 2015; Santiago et al., 2018). In Paragominas, Conservation-development antagonists, who had on average the most remote farms, held the less forest-friendly views, probably since they have to travel long distances through LRs to reach the paved road. However, we also found unfavorable forest views in some small soybean-producing farms (~300 ha) close to the paved road that were managed by Agribusiness-conservation coexistence enthusiasts and Policy complacent-market responders. Since substantial deforestation has taken place near the paved road, landholders here need to lease a forest area to compensate for a LR sometimes distant to their own farm. In several cases we observed that landholders were uninterested about the exact location or state of these rented forests. More resource-endowed landowners of larger landholdings (~2,000 ha) on the other hand, tended to have a more positive perception towards LRs arguably because they have enough cleared areas to expand production and benefit from economies of scale.

Furthermore, the place of birth of landholders can be indicative of the time of arrival to Paragominas which in turn shapes the structure of the farms. For example, a third of Agribusiness-conservation coexistence enthusiasts were early colonizers in the 1970s and 1980s coming from the states of Espírito Santo and Minas Gerais. As a result, they often have large landholdings that have transitioned from cattle ranching to monocultures and are currently a mix of croplands, pastures, and forest. This segment of Agribusiness-conservation coexistence enthusiasts wishes to expand their croplands on accessible fertile, clayey plateaus often covered by forests, as opposed to old pastures in sandy valleys far away from roads. Therefore, although this segment of Agribusiness-conservation coexistence enthusiasts tends to have a positive perception towards LRs, they would like to relocate forests to less fertile soils. On the other hand, Agribusiness-conservation coexistence enthusiasts originating from the southern states of Paraná and Rio Grande do Sul and representing a more recent wave of immigrants (i.e., arrived to Paragominas during the 1990's-2000s to produce soybean), possess smaller areas (400-700 ha) under 5-10 years leasing agreements and their perception towards LR tended to be less positive than the early colonizers. This suggests that the diversity of perceptions towards LR in Paragominas is driven by socio-economic conditions and type of agricultural activity as pointed out for other municipalities in the states of Pará and Mato Grosso (Pacheco et al., 2017b), but also by historical trajectory and remoteness of the landholdings.

4.5.2 Environmental Rural Registry (CAR), property titles and agricultural intensification

One of the most controversial aspects of the policy framework around LR that came up during our interviews was the CAR. Currently, more than 95% of the landholdings in Paragominas are registered in this electronic database (Piketty et al., 2015). The CAR delineates boundaries of landholdings and forest area within the landholding to determine the LR requirement. Landholders' expectations were that after the Green Municipality initiative implemented the CAR, granting of land titles would follow, a process that however did not happen (Piketty et al., 2015). Therefore, CAR among landholders without property titles tends to be perceived as an invasion from the government in the absence of a property title that guarantees land possession. Unregistered properties are not uncommon in the Brazilian Amazon (de Oliveira, 2013), and still can be a delicate topic in Paragominas as the region has a long history of violence and land conflicts as recent as early 2000s (Fernandes, 2011; L'Roe et al., 2016).

Agribusiness-conservation coexistence enthusiasts perceived the lack of property titles as the main barrier for agricultural intensification because it restricts access to credits. One Policy complacent-market responder however, opposed this view: *Everybody blames the lack of property titles, but reality is that nobody wants to change. Productivity is low, stocking rates are minimal, credits have nothing to do with profitability, the property title issue is just an excuse to keep doing things the same way*. Another Policy complacent-market responder argued that: *the agricultural sector has to develop research to make at least two harvests or even three harvests per year feasible. So far, we are competitive because prices are high, but if there is a price crisis, we would be very affected*. Therefore, the perceived barriers for agricultural intensification include the lack of property titles, but also the need for actionable knowledge, agricultural extension services and technical assistance.

4.5.3 Optimizing the landscape or an indecorous proposal?

A recurring topic during our interviews was the idea of a land use exchange mechanism referred to as "troca de areas" (S28 and S29). This term implies reforesting cleared areas and restoring forests on sandy soils unsuitable for soybean production in exchange of clearing degraded forest on fertile clayey plateaus for soybean production. Since the colonization of the municipality in the 1960's took place by extensive cattle ranching, areas of sandy valleys in proximity to water bodies were cleared for cattle to access water. As a consequence, clayey plateaus distant from rivers were left covered by forest that currently have varying degradation levels due to selective logging and forest fires (Martins et al., 2013; Bourgoin et al., 2018).

Most Agribusiness-conservation coexistence enthusiasts shared this view: *for agriculture, this exchange* [troca de areas] *would be very important, it would mean reforesting riparian forests and areas where production is not viable due to distance, topography, and soil quality. Instead, now I have to produce 60 kilometers away from the road rather than being able to work right here*. One Policy complacent-market responder on the other hand, stated*: Do you know what is the real intention behind that idea* [troca de areas]*? Cleared areas on top of plateaus are worth around $R 8,000 per hectare, while areas on top of the plateau covered by forest are worth only between $R400-500. This is an indecorous proposal just to give value to their lands*, and another Policy complacent-market responder stated: *80% of those plateaus covered by forests are in hand of those who lease out the land and not in the hands of those who work the land. Those guys don't want to produce more, they want to lease those areas suitable for production* *because they are not able to lease the valley areas*. These opinions suggest that a "troca de area" can be underlaid by different motives, e.g., to intensify production on mechanizable, fertile soils or to increase the value of land, especially in the case of landholders that lease their land.

In line with Ricardian theory and the von Thünen model (Sills and Caviglia-Harris, 2009), land rent dynamics in Amazon frontiers are influenced by biophysical conditions and distance to markets, but also by agglomeration economies and marketing networks (i.e., firms clustering together generating positive externalities) (Mertens et al., 2002; Garrett et al., 2013). Furthermore, hedonic land rent approaches suggest that forest areas are perceived as a financial burden in the region and influenced by land speculation particularly in connection to infrastructure development (Merry et al., 2008; Sills and Caviglia-Harris, 2009; Miranda et al., 2019). Therefore, a "troca de area" mechanism could indeed increase land rent in Paragominas which in turn could on one hand, incentivize landholders to invest in the owned land (rather than deforesting to expand into new areas), but on the other hand, it could also prompt land speculation, an activity tightly linked to land grabbing and deforestation in the Amazon (Fearnside, 2008; Bowman et al., 2012; Reydon et al., 2020).

A Policy complacent-market responder raised another issue concerning "troca de area": *this [mechanism] would not be a negative incentive for the forest, it would be negative for livestock production [because] it would end meat production in the region as all the valley areas in the municipality are for livestock production*. Land competition between soybean monocultures and pastures can be traced back to the beginning of the Green Municipality initiative in 2008 as the resulting decrease in deforestation limited the amount of open areas close to the paved road (Osis et al., 2019). Possibly, monocultures will be favored on clayey plateaus, until shortage of these areas drive croplands on mechanizable sandy soils in the valleys (Osis et al., 2019). This cropland expansion into sandy valleys was envisioned by Conservation-development antagonists who stressed the need to develop soybean varieties that are high-yielding on sandy soils. Expansion of monocultures into valleys, however, would further increase land competition between soybean and meat production, and potentially with APPs when in proximity to riverbanks.

Although there is currently no policy instrument formalizing land use reallocations such as a "troca de area", landholders in Paragominas are increasingly adopting intensification strategies based on spatial criteria (Plassin et al., 2017). Landholders are intensifying production on available clayey plateaus and abandon less suitable areas to fallows, resembling an incipient process of forest transition (Mather, 1992; Mather and Needle, 1998). Formalizing these existing spontaneous land use reallocation strategies, into voluntary spatial-planning farm protocols could be in principle a tool for forest conservation and restoration. LRs in Paragominas are under constant threat of fire and policies have so far been ineffective to control these due to their multiple drivers and the size of the municipality. Enabling a technical and legal process for assessing possible land use exchanges within a landholding (e.g., "troca de area") could offer an opportunity to actively involve landholders in forest fire prevention and control, as part of an agreement under an authorized voluntary farm protocol for land relocation and forest conservation.

The possible risk of "troca de area" becoming a perverse incentive for deforestation nevertheless, has to be pondered given a recent spike of deforestation in the state of Pará and persisting illegal logging in Paragominas (Cardoso and Souza Jr, 2020; Fonseca et al., 2020). In this regard, it is not clear how landholders define degraded forest and the conservation value of restored forests or the time required to reach a desired conservation stage. Nevertheless, secondary forests are not substitutes for primary forests, and disturbed forest can still retain important biodiversity conservation and carbon storage value (Berenguer et al., 2014; Barlow et al., 2016; Lennox et al., 2018). Another consideration is that "troca de area" could interfere with the CRA system for LR compensation as there are still no clear indications that the CRA can be a sustainable source of income for forestland owners in Paragominas (Brito, 2020). In such case, forest owners would likely opt to substitute forests located in fertile soils for more profitable monocultures if given the option. Therefore, under the current political context where the Federal Government openly opposes regulating agriculture in Amazon (Walker 2019), a "troca de area" could certainly open the door for further deforestation without costs in Paragominas, while the specific conditions under which forest conservation gains are actually possible are not evident.

4.5.4 Further research

Interactions between private and public sector in the context of a frontier landscape can be framed as co-existence, alignment and orchestration (Pacheco et al., 2017). The latter refers to hybrid mechanisms that involve both private and public sectors to trigger landscape transitions that aim at minimizing trade-offs between conservation and production (Pacheco et al., 2017). In Paragominas, important steps towards co-existence and alignment were taken during the

Green Municipality initiative and therefore, next steps towards orchestration should be investigated, aiming at preserving the region's natural capital.

A process of orchestration could provide a platform for negotiation around some of the ideas that we captured such as land use reallocations, but also to discuss related issues that require utmost attention such as forest degradation and fragmentation. One of the focal points of such governance processes at the municipal scale should focus on revalorizing the forest and overcoming the prevalent narrative advanced by ruralists in the region, which frames the forest as an obstacle for rural development (Fearnside, 2017b; Kröger, 2017). Pejorative notions of the forest were clearly manifested by the Conservation-development antagonists' group and at a lesser extent by the Policy complacent-market responders who seemed to prioritize horizontal expansion of agriculture and market demands, and among Agribusiness-conservation coexistence enthusiasts whose "troca the area" proposal seems to prioritize soybean production over forest cover. In this regard, governance initiatives aiming at fomenting productive forest-based systems in Paragominas could learn from the experience of the neighboring municipality, Tomé-Açu, where large-scale agroforestry systems have been successfully implemented by Japanese descendants for the last three decades (Bolfe and Batistella, 2011; Porro et al., 2012). Furthermore, the inclusion of smallholder farmers remains a pending task for future research and environmental governance initiatives in Paragominas (Viana et al., 2016), and the implementation of agroforestry systems at scale could offer opportunities to tackle this.

One of the main limitations attributed to Q methodology is the impossibility to claim external validity in relation to the population of respondents as well as the introduction of biases from the researchers (Kampen and Tamás, 2014). On the other hand, capturing perceptions of LRs in the Brazilian Amazon is a challenging enterprise because of the sensitivity of the topic due to its link to illegal deforestation. The merit of Q methodology in this case was to "smoothen" the interaction with landholders by not asking direct questions about LR but to present an interactive board game with a set of cards exculpating landholders from stating controversial ideas. Furthermore, informal interactions with landholders outside the interview setting allowed us to confirm that the perceptions described in this paper do exist in Paragominas. We do not claim that these are the only views or groups, but the views revealed by our study can already suggest entry points to start discussions aiming at policy interventions towards collective land use management (Dingkuhn et al., 2020).

4.6 Conclusions

In this study we revealed different perceptions among landholders regarding agricultural intensification and Legal Reserves in the eastern Amazon region. Some respondents acknowledged the potential compatibility between Legal Reserves and agricultural intensification but would like to see a more flexible policy framework to relocate Legal Reserves to facilitate agricultural intensification. Other landholders showed a mix of indifference and relative complacency towards Legal Reserves and conservation policies while paying more attention to market demands. A third group of landholders pointed out that taking care of the forest should not be their responsibility and perceive Legal Reserves as an obstacle for agricultural intensification. These different perceptions with regard to Legal Reserve and agricultural intensification are driven by socio-economic factors and ideological and political backgrounds. Such diversity implies that innovative, inclusive, and diverse governance strategies are necessary to engage with different stakeholders into a constructive dialogue to reconcile forest conservation and agricultural intensification. As our results suggests, in order to engage with a diversity of perceptions, such dialogue ought to address land use planning initiatives, developing markets of alternative products (e.g., agroforestry products), and payment for ecosystem services. Revalorization of the forest for its intrinsic and socioeconomic value should be central in this process to harness sustainable agricultural intensification. After deforestation rates have been resurging across the Brazilian Amazon since 2014, local governance towards forest and biodiversity conservation are increasingly needed to structurally decouple agricultural production from deforestation and forest degradation in the long term.

4.7 Acknowledgements

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Appendix

Table 1 Statements, factor score arrays and distinguishing and consensus statements of a Q methodology analysis with 29 landholders. Red shading indicates distinguishing statements for each factor. *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$, ****: $p < 0.0001$.

No.	Statement	F1	F2	F3	Distinguishing factor
1	The CAR is a useful tool to protect Paragominas' biodiversity and nature in rural properties.	2****	-5****	-3*	Distinguishes all
2	LR and APP have a positive effect on productivity, since it obliges landholders to be efficient with the land that is already available.	1****	-4***	-1***	Distinguishes all
3	LR is a burden imposed by the federal government that does not know the local context and prevents my property to be profitable according to my expectations.	-2	-3****	1****	Distinguishes F3
4	The location of LR should be planed to a larger scale than that of a single property taking into account soil conditions and topography to guarantee its positive effect in the whole municipality.	2****	-2****	-2	Distinguishes F1
5	Some areas of my property could be converted into forest, without that causing an economic loss for me and in order to preserve hydrological resources, soils, and biodiversity.	0**	-1	0*	Distinguishes F2
6	In remote areas LR can be a problematic requirement for a landholder due to the risk of land invasion and extractivism of wood and non-wood resources.	1*	0*	-1	Distinguishes F1
7	When a landholder needs to compensate areas of LR outside his or her property he or she has knowledge of what happens in the area that is leased.	-1****	1***	1	Distinguishes F1
8	The money that a landholder stops earning in order to maintain areas of LR is an investment for biodiversity and life quality in Paragominas.	-1***	2***	-3****	Distinguishes all
9	Enrichment planting with fruit trees would be economically interesting if production chains were more consolidated in Paragominas.	3	3***	0****	Distinguishes F3
10	The presence of dwellers in proximity to LR of farms do not increase the risk of forest fires in the LR.	-2****	4	-2****	Distinguishes F2
11	The performance of the municipality concerning the maintenance of roads and bridges is adequate enough for landholder to invest in agricultural intensification.	-5****	5***	-2****	Distinguishes all
12	The duration of land leasing agreements should be defined according to the minimum time that is necessary to consolidate production areas and ensure its viability.	2****	-4**	0****	Distinguishes all
13	The current local, economic, and political context is favorable for investments that allow industrialization and adding value to the products originating in the agribusiness sector of Paragominas.	0****	-3	0****	Distinguishes F2

14	Lack of secure land tenure through property titles to access credits is the main barrier for a landholder in Paragominas to increase production and efficiency.	5****	-2	5****	Distinguishes F2
15	Precision agriculture and silvo-pastoral systems are fundamental technologies for an efficient intensification that should be more applied in Paragominas.	3***	-1	2**	Distinguishes F2
16	The current research projects developed in the region match landholder's demand for information and data.	-3***	0*	-1	Distinguishes F1
17	Pisciculture is a productive activity that will have a great development in the municipality in the upcoming years and I pretend to invest in this sector.	0	1***	3**	Distinguishes F3
18	If the investment capacity of landholders would increase due to credits or government incentives, it would be used mainly for horizontal expansion rather than for vertical integration.	-1****	2	-1***	Distinguishes F2
19	Paragominas does not have comparative advantages in relation to other municipalities of the region.	-4****	3***	-1****	Distinguishes all
20	Currently the work of landholders in the region is valued and has the support of different sectors of society.	-1****	4***	2**	Distinguishes all
21	The agricultural sector of Paragominas has skilled labor and personnel that meets the demands of agricultural and cattle ranching activities.	-4*	-3****	1****	Distinguishes all
22	There is in the region a cultural aspect of entrepreneurial spirit and agricultural culture that allows the development of the municipality's potential.	1****	-2	0**	Distinguishes F2
23	The bureaucracy that surrounds the agricultural sector in Paragominas is excessive and affects its productivity and compliance with environmental legislation.	2****	-1	1**	Distinguishes F2
24	In Paragominas there is certainty in relation to the integrity of rural properties, natural resources, material goods, inputs, and infrastructure.	-2****	0	-2**	Distinguishes F2
25	The lack of effective phytosanitary control of machinery and equipment that come into the municipality from other regions is a source of diseases in my property.	0	1****	4***	Distinguishes F3
26	The use of agrochemicals is a problem for human health and for the environment but given the absence of alternatives I am forced to use these products.	0**	2****	-5****	Distinguishes all
27	Some consumers in Brazil want products free of agrochemical products and that demand could change my production system eventually.	0****	3****	-4****	Distinguishes all
28	Reforesting sandy valleys in exchange of degraded forests due to fire and logging located in clayed plateaus for agricultural production would be optimizing land use according to soil's properties.	4****	-2	3****	Distinguishes F2
29	A mechanism to reforest sandy valleys in exchange for areas with degraded forest due to fire and logging in clayey plateaus, would be a negative incentive to clear areas of primary forest.	-2**	-1*	-4****	Distinguishes all

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30	In areas where the concentration of agricultural land is high, the incidence of pests is less than in areas where agriculture is surrounded by forest and pastures.	-3****	0****	4****	Distinguishes all
31	Paragominas needs a zoning of the agricultural sector to produce in the most profitable areas and conserve in areas where production is not interesting.	3***	1*	2	Distinguishes F1
32	The current policies and governmental mechanisms are efficient to incentivize compliance with the Environmental Regularization Plan and generate a structural network of connected habitats.	-3****	2	-3****	Distinguishes F2
33	Reforesting valleys, where water springs and rivers pass through is necessary to create biological corridors that allow wildlife safe access to water sources.	4****	-1****	1*	Distinguishes all
34	It is necessary to produce technology and varieties to grow grains in sandy valleys with the same productivity that in clayey soils.	1*	0**	3***	Distinguishes all
35	It is important to maintain forest and avoid some agrochemical products to protect bees and pollinators that are important for crop productivity.	1	1	2	Consensus
36	The geography of Paragominas is characterized by areas of low economic potential that have high ecological potential for biodiversity, hydrological services, and carbon storage.	-1	0	0	Consensus

Chapter 5

Exploring land sparing and land sharing strategies to implement tree-based systems and enhance carbon storage in the eastern Brazilian Amazon

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Under review

Abstract

Land sparing and land sharing are two concepts describing contrasting spatial land use allocation strategies to reconcile habitat for biodiversity conservation and agricultural production. So far, the land sparing-land sharing debate has not yet considered other provisioning and regulating ecosystem services, such as carbon storage. Furthermore, assessments of hybrid approaches beyond this apparent dichotomy are scarce. Here we explore potential effects of different landscape structures on carbon storage in the soil and in aboveground biomass in the municipality of Paragominas, eastern Amazon. We collected secondary data from the literature and applied the spatially explicit Carbon Storage and Sequestration InVEST model to estimate carbon storage for eight landscape configuration and composition scenarios. Each scenario was underpinned by a land sparing or land sharing strategy and distinctive management priorities. Three scenarios represented an increase of carbon stocks in relation to the 2015 baseline, i.e., the Natural forest regeneration scenario (+14.3%), the Cocoa-oil palm-based agroforestry scenario (+2.4%) and the Hybrid mosaic landscape scenario (+10.6%). Scenarios in which agricultural expansion resulted in deforestation indicated substantial carbon losses (-12.7 and -40.6%), while scenarios based on Paricá-fruit tree agroforestry and agro-silvo-pastoral systems resulted in small carbon losses (-1.3 to -4.6%). Our results highlight the importance of natural regeneration of secondary forests as a management strategy to enhance carbon storage. Our scenarios also highlight that strategies that combine a land sparing and land sharing approach may be useful to inform policy-making decisions towards landscape multifunctionality in an Amazonian frontier.

Key words: Land sparing, land sharing, land use allocation, carbon storage, landscape scenarios, landscape multifunctionality, eastern-Amazon

5.1 Introduction

There is a long-standing and ongoing debate about land use management strategies to reconcile agricultural production and biodiversity conservation, in which the land sparing and the land sharing paradigms have been central (Green et al., 2005; Fischer et al., 2008; Perfecto and Vandermeer, 2010; Phalan et al., 2011a; Phalan et al., 2011b; Tscharntke et al., 2012; Fischer et al., 2014; Kremen, 2015; Phalan, 2018). Land sparing refers to the spatial segregation of biodiversity conservation from agricultural production, while land sharing favors the spatial integration of "wild-life friendly farming" and biodiversity conservation within heterogenous landscapes (Green et al., 2005; Fischer et al., 2008; Fischer et al., 2014). The land sparing paradigm assumes that agricultural intensification in specific areas enables to free up land for biodiversity conservation, while land sharing should support species tolerant to disturbances in less-intensive farming landscapes (Law et al., 2015). Models beyond this apparent dichotomy, however, are scarce but may be useful to inform realistic land use policies that aim at fulfilling increasing societal demands from agricultural landscapes without compromising environmental sustainability (Kremen, 2015; Renwick and Schellhorn, 2016; Meli et al., 2019).

The land sparing-land sharing debate has mostly focused on the relationship between agricultural productivity and biodiversity conservation. Carbon storage on the other hand, is the prime ecosystem service that regulates climatic functions that maintain the ecological processes that support life (Leemans and De Groot, 2003). Deforestation and forest degradation are major anthropogenic sources of carbon emissions in the atmosphere, corresponding to 6-25% of the global emissions through forest biomass combustion and decomposition of plant material and soil carbon (Baccini et al., 2012; Pearson et al., 2017). However, the potential impacts of land sparing (i.e., intensification of agricultural productivity on existing farmland limiting the conversion of natural habitats) or land sharing (i.e., enhancing ecological processes to support agricultural production in heterogenous, less-intensive farming landscapes) strategies on carbon storage in agricultural landscapes remain unclear (Williams et al., 2018). Furthermore, most studies that focus on the land sparing-land sharing debate remain mostly theoretical and do not consider specific land use or management options. Such information is essential to inform actionable and context-specific policy recommendations.

The spatial heterogeneity of landscapes is defined by their structure, which entails landscape composition and configuration (Klingbeil and Willig, 2009). Landscape composition describes the relative proportion of different land use and land cover (LULC) classes, while landscape configuration describes their spatial arrangement (Klingbeil and Willig, 2009). Within the structure of a rural landscape, agricultural land surrounding patches of natural vegetation form the 'matrix' of the landscape (Driscoll et al., 2013). Therefore, tree-based systems can influence spatial landscape heterogeneity with the concomitant enhancement of carbon storage capacity (Bambrick et al., 2010). Nevertheless, the effects of implementing tree-based systems at scale on carbon storage are still unknown in the Amazon region.

The aim of our study was to assess the effects of landscape structure following different land sparing and land sharing strategies centering around tree-based systems on aboveground and belowground carbon stocks in the eastern Amazon region. For this purpose, we reviewed in the literature for tree-based systems that may have the potential to reconcile agricultural production and carbon storage, and then explored eight different landscape scenarios based on these systems reflecting different land sparing and land sharing formats. We used a 2015 LULC map of our study as baseline, and we reclassified LULC categories in our scenarios reflecting different priorities and strategies for a 15-years period. The implications of the eight scenarios for carbon storage can be useful to inform landscape management and policy-making to enhance carbon storage and overall landscape multifunctionality in the eastern Amazon region.

5.2 Methods

5.2.1 Study site

The study region was the municipality of Paragominas (19,342 km²) in the northeastern region of the Pará State, Brazil. The municipality was founded in 1965 and as a typical frontier town in the eastern Amazon its history has been characterized by deforestation, timber extraction and extensive beef cattle production (Toniolo and Uhl, 1995). More recently, in the early 2000s, soybean monocultures and eucalyptus plantations were introduced, particularly near the urban center and federal highway BR-010 (Piketty et al., 2015). Large-scale deforestation has been under control in Paragominas since 2010 after a social pact, known as the Green Municipality initiative, was signed by the major actors of the local agricultural sector prompting agricultural intensification in available open areas (Piketty et al., 2015). Currently, approximately 65% of the Paragominas territory is still covered by forest, but some of these are degraded by fires and selective logging (Berenguer et al., 2014; Nunes et al., 2014; Bourgoin et al., 2018). Around half of the municipality consists of pastures and agriculture in marginal areas, and regenerating or degraded forest (Pinillos et al., 2020). The landscape of Paragominas is also characterized by a topographical and pedo-morphological mosaic pattern shaped by clayey plateaus separated by sandy valleys of up to 12 kilometers wide, where floodplains spread along a dense river network (Laurent et al., 2017).

In terms of landownership, Paragominas is one of the municipalities in the region with one of the highest levels of land concentration, and the average property size ranges between 800-1,000 ha (Simmons, 2004; Viana et al., 2016). As in all municipalities in the Brazilian Amazon (i.e., Amazônia Legal), rural properties in Paragominas are required to keep 80% of their land under native forest cover known as Legal Reserves (Lei no. 12.651, Native Vegetation Protection Law). This law also stipulates areas of permanent preservation (APPs for its acronym in Portuguese) prohibiting the removal of vegetation along rivers and steep slopes and hilltops. State legislation in Pará, nevertheless, allows a reduction of the proportion of Legal Reserves down to 50% in certain denominated consolidation zones defined by the Ecological-Economic Zoning Plan. Therefore, depending on its location and forest liability status, a rural property in Paragominas is required to have a Legal Reserve proportion ranging from 50-80%. This legal, biophysical, and historic context renders Paragominas a region with complex land use dynamics involving agricultural intensification and forest conservation.

5.2.2 Land use and land cover management and carbon storage in Paragominas

5.2.2.1 Conservation of primary forests

Primary forests are more resilient and able to store larger amounts of carbon than young, degraded or planted forests (IPCC, 2019). It is estimated that the forests of the Amazonian basin store 90-140 billion tons of carbon (Soares-Filho et al., 2006). In Paragominas, primary forests store an estimated 142 million tons of carbon in the above and belowground biomass corresponding to approximately 200 ton C ha^{-1} (Pinillos et al., 2020). Aside from other functions supported by primary forests, the carbon storing function alone merits conservation measures to prevent deforestation and anthropogenic disturbances caused by selective logging and forest fires (Berenguer et al., 2014; Barlow et al., 2016). Avoiding deforestation can have positive impacts on agricultural intensification in the region as investments for expansion of agricultural lands can shift towards farm intensification (Koch et al., 2019). Large portions of primary forests in Paragominas are, however, located on clayey plateaus which are suitable for soybean production and thus are potentially threatened by agricultural expansion (Pinillos et al., 2020).

5.2.2.2 Forest restoration in degraded forests

Naturally regenerated forests in Paragominas represent only 18% of the total forest area that is required by law along riparian areas, highlighting the need to actively restore APPs and Legal Reserves in Paragominas (Nunes et al., 2014). Forest restoration entails the introduction of tree species in degraded forests without eliminating existing species (i.e., forest enrichment). Pilot initiatives in Paragominas have demonstrated the potential of forest recovery by the introduction of native hardwood and fruit tree species in Legal Reserves on marginal land (Diederichsen et al., 2017). Forest restoration strategies may also use a mix of commercial exotic and native successional species (Parrotta and Knowles, 1999). Forest restoration should also focus on riparian forests as these are crucial to maintain water quality and habitat connectivity in the region. Despite strict legal regulations, deforestation in Paragominas has also taken place along riparian areas in proximity to the paved roads to provide water access to cattle (Nunes et al., 2014). Rates of carbon sequestration in regenerating forest of the Amazon vary depending on age, regeneration stage and tree species composition particularly with regard to pioneer tree species (Lucas et al., 2002).

5.2.2.3 Re-agroforestation of degraded lands

Re-agroforestation refers to reforesting land with agroforestry systems (Michon et al., 2000). In Paragominas this could be applicable in unmanaged pastures and abandoned secondary forest where the implementation of agroforestry systems can enhance carbon storage, habitat for biodiversity and agricultural production from tree-based systems. Cocoa (*Theobroma cacao*) agroforestry systems, for instance, have been successfully implemented in abandoned cleared lands in southern Pará, thereby increasing above and belowground carbon stocks (Schroth et al., 2016). The municipality of Medicilândia is the largest cocoa producer in Pará with a production of 16.4 million tons in 2017, while cocoa production in Paragominas was only 40,000 tons in the same year (IBGE, 2017), suggesting ample room for increasing cocoa production in Paragominas. Furthermore, cocoa agroforests can provide suitable habitat conditions for fauna, such as ferns, frogs, lizards, birds and bats, as shown in the state of Bahia (Faria et al., 2007), as well as enhance natural pest control (Delabie et al., 2007). Cocoa agroforestry systems can be enriched with local timber species (e.g., paricá (*Schizolobium amazonicum*), andiroba (*Carapa guianensis*), bandarra (*Parkia paraensis*), cedro (*Cedrela odorata*), cerejeira (*Torresea acreana*), freijo (*Cordia alliodora*) and mahogany (*Swietenia macrophylla*)), and tree crops (e.g., cupuacu (*Theobroma grandiflorum*), pupunha palm (*Bactris gasipaes*), açai palm (*Euterpe olercea*), araçá-boi (*Eugenia stipitata*), acerola (*Malphighia punicifolia*), lemon (Citrus spp.) and orange (*Citrus sinensis*)) to support secondary forest succession, the associated benefits of enhancing carbon storage and the provision of habitat for biodiversity (Browder et al., 2005).

Furthermore, in 2012, modifications in the new Forest Code (Native Vegetation Protection Law Lei 12.651) allowed compensation of forest areas with agroforestry systems that may contain up to 50% of exotic species. The extent to which exotic species can fulfil the functionality of natural forests to store carbon and provide habitat for biodiversity is related, among other factors, to tree density and surrounding land cover. For instance, agroforestry systems with a teak (*Tectona grandis*) density of less than 20% in combination with native fruit trees supported populations of ungulate and forest-dwelling primates when remnants of primary forests were located near the agroforestry systems (Oliveira et al., 2019). Thus, the use of valuable, rapid growing exotic species in agroforestry systems may offer an efficient strategy to enhance carbon storage, habitat for biodiversity, and timber and fruit production in agroforestry systems located in formerly unmanaged or degraded areas in Paragominas.

5.2.2.4 Integrated agro-silvo-pastoral systems

The federal plan for Low Carbon Agriculture (Plano ABC) stipulates integrated agricultural systems in different forms (i.e., agro-pastures, agroforestry, silvo-pastures and agro-silvo-pastures) as an important strategy to meet voluntary national targets to reduce greenhouse gas (GHG) emissions (EMBRAPA, 2011). Integrated crop-livestock systems (ICLS for its acronym in Portuguese) entail the periodic rotation of crops and pastures on the same area (Gil et al., 2016). These systems are usually established on degraded pastures that undergo liming, fertilization, and ploughing for the cultivation of soybean during 2-5 years followed by re-establishing pastures (Nepstad et al., 2019). ICLS can be a strategy to increase agricultural production without additional forest clearing and without land use displacement, while at the same time increasing the quantity and quality of soil organic carbon in comparison with continuous cropping (de Oliveira et al., 2014). For instance, the implementation of ICLS increased carbon stocks in the 0- 30 cm soil layer in the order of 0.36 Mg ha yr^{-1} in the Cerrado (Carvalho et al., 2014). Furthermore, ICLS can improve nutrient cycling and enhance biodiversity (Lemaire et al., 2014).

Agro-silvo-pastoral systems (ILPF for its acronym in Portuguese) may store even more carbon than ICL systems because tree species can immobilize higher amounts of carbon and for longer periods than crops or pastures (Jose, 2009; Nair et al., 2011). In the state of Mato Grosso, for example, ILPF stored 5 tons C ha^{-1} year $^{-1}$ or 18-tons ha^{-1} CO_2, which is equivalent to the GHG emissions of 12 adult cattle heads ha $^{-1}$ $year^{-1}$ (Ofugi et al., 2008). Furthermore, ILPF systems contributed to an increase in agricultural output by 25% between 2006 and 2012 without the need to clear forests in Mato Grosso (Balbino et al., 2011; Macedo et al., 2012; Luciano et al., 2017). In terms of food production and economic returns, it is expected that integrated agricultural systems in the Amazon can perform better than extensive or rotational pasture systems (Gil et al., 2018). Furthermore, due to their higher botanical diversity and structural complexity, integrated systems can be more resilient to climate change conditions than non-integrated systems (Gil et al., 2017).

5.2.3 Quantifying carbon storage in the Paragominas landscape

We used the Carbon Storage and Sequestration InVEST 3.7.0 model (Sharp, 2020) to assess carbon storage at the landscape scale in Paragominas. This spatially explicit model has been widely used for the quantification of carbon storage at a regional scale (Azevedo et al., 2017; Zhang et al., 2017; Pavani et al., 2018; Pechanec et al., 2018; Sun et al., 2018; Xiang, 2018; Zarandian et al., 2018; Li et al., 2020). The model aggregates the amount of carbon stored in four carbon pools (aboveground living biomass, belowground living biomass, soil organic matter, and litter) based on LULC raster maps. In our study we considered only carbon in aboveground biomass and soil organic matter. In tropical regions these two pools alone contain roughly half of the landscape carbon stocks (Watson et al., 2000). Moreover, aboveground carbon and soil carbon are the most vulnerable pools to land use change in the Amazon (Berenguer et al., 2014). The carbon stocks for the different LULC classes were estimated using secondary data (Table 5.1). For forests LULC classes (i.e., undisturbed, degraded, highly degraded and secondary forests), pastures and cropland, secondary data were obtained from studies previously used in Pinillos et al., 2020 to model ecosystem services provision. For agroforestry systems (Paricá and fruit tree agroforestry and oil palm-cocoa agroforestry) we conducted a search in Web of Science (TOPIC: ("carbon stock*") AND TOPIC: (agroforestry) AND TOPIC: (eastern amazon*)) that delivered seven studies. We selected three studies based on similarities and relevance for our scenarios (i.e., Oxisols, samples taken at 0-30 cm depth, age of the system and closeness to Paragominas). For ILPF, we found one study conducted in Paragominas on soil carbon stocks and another study on aboveground biomass (Table 5.1).

Table 5.1 Carbon storage (tons ha^{-1}) in soil organic matter and aboveground biomass for selected land use and land cover classes.

Land use and land cover class	Location*	Soil type	Soil organic carbon at (tons C ha^{-1}) 0-30 cm	Carbon in aboveground biomass (tons C ha^{-1})	Total carbon (tons C ha^{-1})	Source
Undisturbed forest	Paragominas, Pará (Amazon biome)	Sandy Oxisols	43.0±2.5	204.8 ±13.4	247.8	Berenguer et al. (2014)
Degraded forest	Paragominas, Pará (Amazon biome)	Clayey Oxisols	63.5 ±3.7	133.9 ± 6.3	197.3	Berenguer et al. (2014)
Highly degraded forest	Paragominas, Pará (Amazon biome)	Clayey Oxisols	60.8 ±3.5	88.7 ± 6.1	149.5	Berenguer et al. (2014)
Secondary forest	Paragominas, Pará (Amazon biome)	Clayey Oxisols	60.3 ±4.3	49.7 ± 5.9	110.0	Berenguer et al. (2014)
Pasture	Santarém, Pará (Amazon biome) Jamari, Rondônia (Amazon biome)	Sandy Oxisols	52.7 ±1.1	33.5 ± 6.8	86.2	Guild et al. (1998); Durigan et al. (2017)
Cropland (soybean monocultures)	Santarém, Pará (Amazon biome)	Clayey Oxisols	46.2 ±1.4	0.00	46.2	Durigan et al. (2017)
Paricá (*Schizolobium amazonicum*) and fruit tree agroforestry	Mãe do Rio, Pará (Amazon biome) São Luís, Maranhão (Amazon biome)	Sandy Oxisols	38.7±3.1	30.9 ± 23.3	68.9	Lemos et al. (2016); Celentano et al. (2020)
Oil palm-cocoa agroforestry	Tomé-Açu, Pará (Amazon biome)	Sandy Oxisols	62.6 ±3.2	47.7 ± 1.8	110.3	Ramos et al. (2018)
Crop-livestock-forest integration system (ILPF for its Portuguese acronym)	Paragominas, Pará (Amazon biome) Paracatu, Minas Gerais (Cerrado biome)	Clayey Oxisols	41.70	63.5	105.2	Fernandes et al. (2019); Tsukamoto Filho et al. (2004)

* When two locations are indicated, the first one corresponds to the soil pool and the second one to the aboveground biomass pool.

5.2.4 Landscape scenarios for Paragominas

We used the InVEST model to evaluate the effectiveness of implementing tree-based systems by comparing carbon stocks of a LULC map of the current (baseline) landscape and LULC maps of future scenarios. Scenarios represent projections of the future that are not necessarily predictions but rather alternative representations of how the future might unfold in order to improve our understanding of complex human-environment systems (Nakicenovic and Swart, 2000). Scenario analysis is a useful tool to assist policy-making because it can provide insights about future consequences of current management and policy decisions (Nakicenovic and Swart, 2000; Alcamo, 2008). Scenarios can be classified as exploratory or anticipatory (Alcamo et al., 2001). Exploratory scenarios describe future trends based on mathematical models with a forward progression of time. Anticipatory scenarios, on the other hand, are prescribed indicative images of the future aligning with a particular vision of the future (Alcamo et al., 2001). Here, we adopt an anticipatory scenario approach.

Our scenarios build on a landscape classification of Paragominas into landscape units identified according to combinations of pedo-morphological (i.e., clayey plateaus, sandy valleys and sandy floodplains) and LULC categories as the two main biophysical drivers of carbon storage (Pinillos et al., 2020). This landscape classification revealed areas of land degradation, signaling possible underutilization of the land in terms of carbon storage, agricultural production, and habitat for biodiversity. These areas cover roughly half of the municipality (1 million ha) and consist mainly of pastures and cropland in marginal areas (e.g., floodplains and escarpments) which are prone to soil erosion, and by degraded and regenerating secondary forests (Pinillos et al., 2020).

Based on this landscape classification, we generated eight anticipatory scenarios ranging across a spectrum from a production-oriented to a conservationist vision of the landscape (Table 5.2):

1. *Massive agricultural-livestock expansion* (S1): all forests are converted to soybean monoculture or pastures;
2. *Agricultural livestock-expansion* (S2): degraded forests and highly degraded forests are converted to soybean monoculture or pastures;
3. *Natural regeneration* (S3): all forests are conserved including secondary forests for natural regeneration;
4. *Paricá-fruit tree agroforestry* (S4): pastures in marginal areas and secondary forests are converted to paricá (*Schizolobium amazonicum*)-fruit tree agroforestry systems;

5. *Cacao-oil palm agroforestry* (S5): pastures in marginal areas and secondary forests are converted to cacao-oil palm (*Elaeis guineensis)* agroforestry systems;
6. Agro-silvo-pastoral systems*, ILPF* (S6): pastures in marginal areas are converted to ILPF and secondary forests are converted to paricá-fruit tree agroforestry systems;
7. *Massive* agro-silvo-pastoral systems *ILPF* (S7): all pastures are converted to ILPF and secondary forests are converted into paricá-fruit tree agroforestry systems;
8. *Hybrid mosaic* (*S8)*: pastures in marginal areas are converted to paricá-fruit tree agroforestry systems, and secondary forests undergo natural regeneration.

The 'Massive agricultural-livestock expansion' and the 'Agricultural livestock-expansion' scenarios prioritize the expansion of agricultural land, while on the other side of the spectrum the 'Natural regeneration scenario' prioritizes forest conservation and natural forest regeneration. In between these two ends, we included scenarios where integrated agricultural systems in different forms (i.e., agroforestry and agro-silvo-pastoral systems) are implemented. Finally, the 'Hybrid mosaic landscape scenario' follows a "both-and" approach characterized by large fragments of forest and a landscape matrix shaped by land sharing patterns (Kremen, 2015). The scenarios consider a 15-year period from our 2015 baseline, in accordance with the intended Nationally Determined Contribution (NDC) objectives to reduce GHG emissions by 43% in 2030 in relation to the 2005 levels (Brazil, 2015).

5.2.5 Simulating land use and land cover changes under different landscape scenarios

We designed eight LULC maps for Paragominas in 2030 at a spatial resolution of 630 x 630 m. Using ArcGIS10.4.1, each grid cell in the 2015 LULC raster map was assigned a one-digit reclassification of LULC change representing the LULC category for 2030. The LULC reclassification rules for the respective scenarios are shown in Table 5.2. The LULC maps for each scenario in 2030 were used as inputs for the InVEST model to calculate carbon storage in the aboveground biomass and in the soil at grid cell level.

Table 5.2 Anticipatory landscape scenarios in Paragominas, LULC reclassification rules, management priorities and underlying visions.

Scenario	LULC reclassification	Management priority	Vision
1) Massive agricultural-livestock expansion	• All forests on clayey plateaus are converted to cropland (soybean). • All forests on sandy valleys are converted to pastures. • All floodplains are converted to secondary forest.	Priority is expansion of traditional agricultural systems (i.e., soybean monoculture and pastures). Agricultural areas expand at the expense of forest.	Forest conservation in private properties is considered a burden by farmers who would like to eliminate Legal Reserves.
2) Agricultural-livestock expansion	• Degraded and highly degraded forests on clayey plateaus are converted to cropland (soybean). • Secondary forests are converted to pastures. • All floodplains are converted to secondary forest.	Idem	Idem
3) Natural regeneration	• Pastures are converted to secondary forest. • Secondary forests are conserved and are classified as highly degraded forest*.	Priority is forest conservation and forest regrowth in a land sparing pattern.	Forest should be strictly conserved, and areas of natural regeneration left untouched to allow ecological succession.
4) Paricá -fruit tree agroforestry	• Pastures in marginal areas are converted to paricá-fruit tree agroforestry. • Secondary forests are converted to paricá-fruit trees agroforestry.	Priority is re-agroforestation of degraded areas in a land sharing pattern.	Diversification of agricultural systems and development of markets for agroforestry products in the region.
5) Cocoa-oil palm agroforestry	• Pastures in marginal areas are converted to cocoa-oil palm agroforestry. • Secondary forests are converted to cocoa-oil palm agroforestry.	Idem	Idem

6) Agro-silvo-pastoral systems ILPF	• Pastures in marginal areas are converted to ILPFs. • Secondary forests are converted to paricá-fruit tree agroforestry.	Priority is intensification of unmanaged areas in a land sharing pattern.	Diversification of agricultural production using technologies supported by the Low Carbon Agriculture government plan.
7) Massive agro-silvo-pastoral systems ILPF	• All pastures are converted to ILPF. • Secondary forests are converted to paricá-fruit tree agroforestry.	Priority is intensification of all pastures in a land sharing pattern.	Idem
8) Hybrid mosaic	• Pastures in marginal areas are converted to paricá-fruit tree agroforestry. • Secondary forest is classified as highly degraded forest*.	Priority is natural regrowth of secondary forests in a land sparing pattern, and re-agroforestation of unmanaged areas in a land sharing pattern.	No identified social actor explicitly ascribing to this vision.

* This reclassification assumes that a secondary forest in Paragominas undergoes floristic reassembly and succession in tree species composition (Norden et al., 2009; Mesquita et al., 2015) during a 15-year period to match a highly degraded forest (i.e., burnt and logged) in terms of carbon storage. This presumes a growth rate of 2.6 Mg C ha^{-1} $year^{-1}$ for the two pools assessed in this study, which is four times lower than the presumed growth rate in Brazil's second national forest inventory regarding forest biomass in Amazonian secondary forests (Fearnside, 2018).

5.3 Results

The eight scenarios resulted in contrasting levels of carbon storage. Three scenarios represented an increase of carbon stocks as compared to the 2015 baseline. These were S3 (Natural regeneration) with a 14.3% increase, S5 (Cocoa-oil palm agroforestry) with a 2.4% increase, and S8 (Hybrid mosaic) with a 10.6% increase. S1 and S2 (Massive agricultural-livestock expansion and Agricultural-livestock expansion scenarios) represented a loss of 40.6 and 12.7% of carbon stocks, respectively. The other scenarios indicated a net loss of carbon stocks as compared to the 2015 baseline ranging from 1.3-4.6 % (Table 5.3).

The scenarios with a positive balance (S3, S5 and S8) maintained higher carbon stocks in the eastern and western parts of the municipality under forest cover, while generally maintaining a landscape matrix with higher carbon stocks than the other tree-based scenarios (S4, S6 and S7). S2 showed carbon losses mainly in areas proximate to the main road, while S1 showed a homogenous depletion of carbon stocks across the entire municipality (Figure 5.1).

Table 5.3 Carbon storage for the different LULC scenarios and its relative change compared to the 2015 baseline scenario.

No.	Scenario	Total landscape carbon stocks (Million-ton C)	Δ Million-ton C relative to baseline	Δ % relative to baseline
Baseline		**278.7**	**-**	**-**
S1	Massive agricultural-livestock expansion	165.5	-113.2	-40.6%
S2	Agricultural-livestock expansion	243.4	-35.3	-12.7%
S3	Natural regeneration	318.6	+39.9	+14.3%
S4	Paricá-fruit tree agroforestry	265.8	-12.9	-4.6%
S5	Cocoa-oil palm agroforestry	285.4	+6.7	+2.4%
S6	Agro-silvo-pastoral systems, ILPF	274.2	-4.5	-1.6%
S7	Massive agro-silvo-pastoral systems, ILPF	275.2	-3.6	-1.3%
S8	Hybrid mosaic	308.3	+29.6	+10.6%

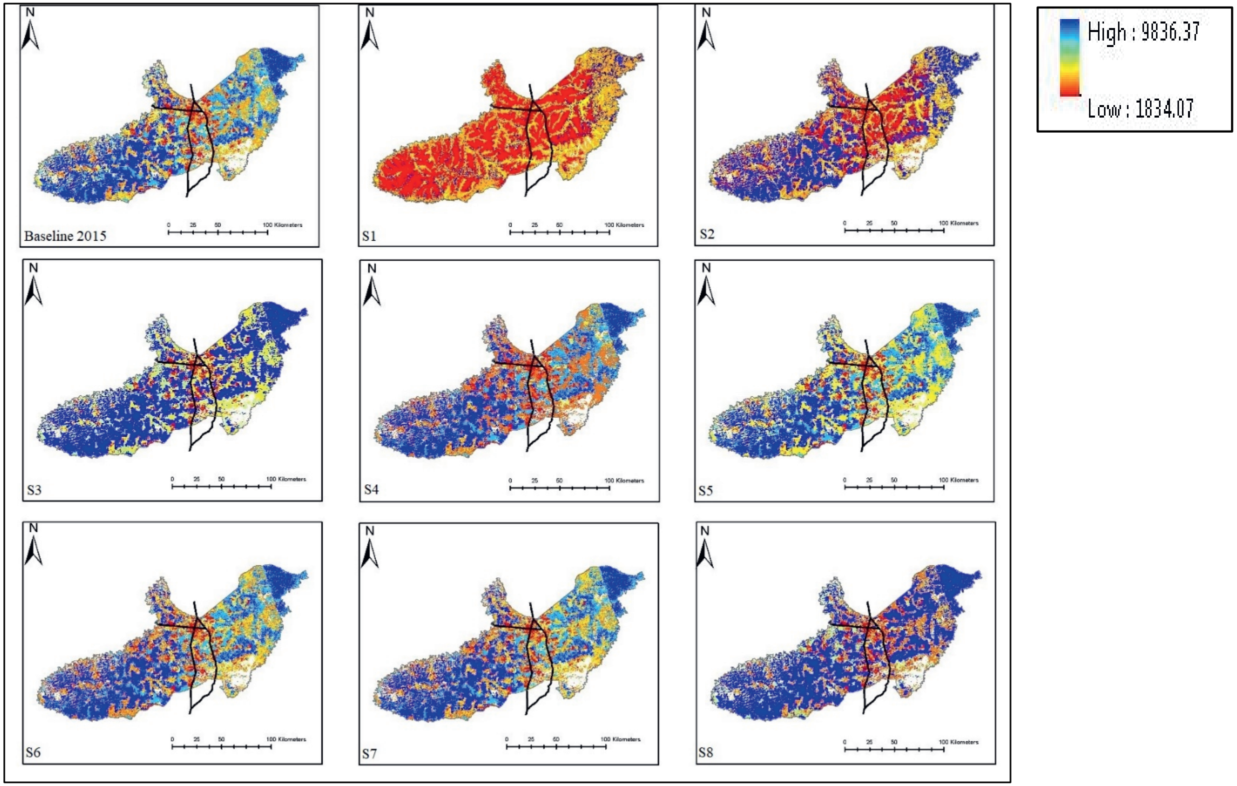

Figure 5.1 Maps of carbon stocks (tons C per grid cell) for the 2015 baseline and eight land use land cover anticipatory scenarios. From left to right; top row: 2015 baseline, S1. Massive agricultural-livestock expansion, S2. Agricultural-livestock expansion; mid row: S3. Natural regeneration, S4. Paricá-fruit tree agroforestry, S5. Cacao-oil palm agroforestry; bottom row: S6. Agro-silvo-pastoral systems, ILPF, S7. Massive ILPF, S8. Hybrid Mosaic scenario. Legend indicates carbon stocks per grid cell in tons, equivalent to 247.8 (High) and 46.2 (Low) tons ha^{-1}.

5.4 Discussion

In this study we explored the effect of eight land use land cover scenarios reflecting different land management objectives influencing the landscape's capacity for carbon storage in the municipality of Paragominas, eastern Amazon. The Natural regeneration scenario (S3) followed a land sparing strategy prioritizing nature conservation and the expansion of forest areas. While this scenario gave rise to the highest carbon storage (14.3 %), it implied that most unmanaged areas of the municipality are destined for natural regeneration of secondary forests. In reality, however, deforestation rates in the Amazon have been increasing since 2014 following continuing high demands of agricultural commodities and the loosening of environmental legislation (Sauer, 2018; Fonseca et al., 2020). The Massive agricultural-livestock expansion (S1) and the Agricultural-livestock expansion scenarios (S2) where agriculture expands into forest areas at different degrees, represented substantial carbon losses of 40.6 and 12.7 %, respectively. Although agricultural expansion into forest areas is illegal, recent spikes in deforestation across the eastern Amazon region (Fonseca et al., 2020) suggest that agricultural expansion in detriment of primary and secondary forests with concomitant carbon losses cannot be ruled out in Paragominas. On the other hand, land sharing strategies in the form of agroforestry and integrated crop-livestock systems were explored in scenarios S4-S7 (i.e., Paricá-fruit tree agroforestry, Cocoa-oil palm agroforestry, ILPF and Massive ILPF), but only Cocoa-oil palm agroforestry (S5) resulted in a small increase of carbon stocks (2.4% in relation to the 2015 baseline). The other agroforestry scenarios led to a decrease of carbon stocks (ranging from 1.3-4.6 % as compared to the 2015 baseline) as agroforestry systems were prioritized over natural regeneration of secondary forests. This finding underlines the importance of preserving secondary forest as a low-cost management strategy to enhance carbon storage in the landscape (Dupin et al., 2018). The importance of secondary forests for carbon storage was further supported by the Hybrid mosaic landscape scenario (S8), where the mix of agroforestry systems, secondary forest recovery and conservation of undisturbed forest signified a 10.6 % increase of carbon storage relative to the 2015 baseline.

The hybrid land use strategy (S8) illustrated the consequences of introducing trees in unmanaged and degraded areas with higher potential for carbon storage than the traditional agricultural systems (i.e., soybean monoculture and pastures). Therefore, by combining land sparing and land sharing strategies, i.e., large undisturbed forests, croplands and productive pastures, agroforestry systems, and secondary forest, S8 portrays a hybrid landscape with the potential to enhance overall landscape multifunctionality in Paragominas through the accommodation of tree/forest cover in the agricultural matrix (Perfecto and Vandermeer, 2010). This scenario responds to the call for further exploration to enhance landscape restoration by expanding tree cover in tropical agroecosystems (Meli et al., 2019).

5.4.1 Coordinated landscape management to enhance landscape multifunctionality

The simulated land use changes in our eight scenarios were based on a landscape classification informed by pedo-morphological categories (topography, soil texture and proximity to rivers) and LULC classes (Pinillos et al., 2020). These scenarios, however, did not account for farm boundaries. This aspect is one of the main challenges of landscape management because while conservation strategies ought to consider the landscape ecosystem as a whole, the structure of agricultural landscapes and associated ecosystem services is to a large extend shaped by management decisions of individual land managers and farmers (Polasky et al., 2011). Therefore, a key consideration to attain multifunctionality in agricultural landscapes is how to elicit coordinated landscape management across farm boundaries.

Landscape management needs to account for the spatial allocation of land uses because this is a major factor of landscape structure and consequently of the supply of ecosystem services (Gomes et al., 2020). In this regard, economic incentives appealing to the decision-making of farmers and landholders to foment coordinated spatial land use allocation following a common objective (e.g., increasing carbon storage) is a key component of landscape management policies. Agglomeration mechanisms, for example, aim to create contagious habitats across private properties to avoid habitat fragmentation (Parkhurst et al., 2002; Smith and Shogren, 2002). In principle, such mechanisms are designed as a bonus that rewards farmers for each unit of area left for habitat conservation (i.e., retired area) sharing a common border with another retired area, either on the same or on the neighboring property. Thus, by paying landowners for a shared border each landowner has an explicit incentive to voluntarily retire an area adjacent to another retired area (Parkhurst et al., 2002).

In Paragominas, a policy tool based on rules that includes carbon storage targets and compensates for shared borders across farms, could have two payment modalities: one that rewards retiring land for forest regeneration and conservation, and a second payment type for implementing agroforestry systems. This mechanism could potentially incentivize an individual farmer to implement agroforestry in underutilized areas of his/her farm, as well as neighboring farmers with adjacent areas, ultimately increasing carbon stocks in the landscape matrix. In turn, enhanced carbon stocks in the aboveground biomass could also improve habitat connectivity by creating agro-forestry corridors and connecting forest patches, while higher soil carbon stocks could also improve soil fertility.

The new Forest Code (Native Vegetation Protection Law Lei 12.651) already stipulates a Payment for Ecosystem Services (PES) scheme. The Environmental Reserve Quotas (CRA for its acronym in Portuguese) is a forest trading mechanism under development that allows landowners who illegally deforested before 2008 to be absolved by purchasing CRA from landowners who have conserved more forest than required by law. Initial estimates in the state of Pará indicate that the supply of CRA exceeds the areas with illegal deforestation (i.e., forest debt) as much as by a factor of five (Soares-Filho et al., 2014; Nunes et al., 2016). However, when considering the legal status of properties, this oversupply decreases by more than half because legislation does not allow the use of forest surpluses from non-titled lands (Brito, 2017). While more than 95% of the private landholdings are registered in the Environmental Rural Registry (CAR for its acronym in Portuguese) in Paragominas, very few have a definitive land title (Piketty et al., 2015).

The effectiveness of the CRA to incentivize forest conservation will depend to a large extent on the financial value of the forest quotas, which will in turn depends on CRA supply levels (i.e., an oversupply would lower prices reducing incentives to restore forests) (Brito, 2017; 2020). Even if effectively implemented, the CRA is a spatially implicit trading system and therefore unsuitable to incentivize coordinated landscape management (e.g., spatial land use allocations across farm boundaries following a common goal). Therefore, including a spatial mechanism, such as an agglomeration bonus, within the existing policy framework could catalyze landholders' coordinated land use decisions towards a common landscape objective (e.g., increase carbon storage and create biodiversity friendly corridors in productive systems).

The financial viability of agroforestry systems is another critical aspect for any prospects of implementing these systems at the landscape scale in Paragominas. One of the main barriers for its implementation is the shortage of local processing, storage, marketing facilities and access to seeds and seedlings in the region (Browder et al., 2005; Nunes et al., 2020). On the other hand, large-scale agroforestry systems could tackle the pending inclusion of smallholders in municipal initiatives, as agroforestry are labor-intensive systems that can be a source of jobs and income for smallholders. Thus, municipal initiatives aiming at creating more heterogenous, hybrid land sparing-land sharing, landscapes, could promote land use planning that limits monocultures expansion and fosters a forest-based economy that is able to enhance landscape multifunctionality (Stabile et al., 2020).

5.4.2 Further research directions

In this study we used carbon storage as an indicator to assess the ecological performance of different landscape composition and configurations. Although carbon storage can be a proxy to assess habitat for biodiversity and associated ecosystem services under certain conditions (Freudenberger et al., 2012; Manhaes et al., 2016), distinct targets and indicators are necessary in order to assess different ecosystem services as spatial correlations may not be sufficient to effectively protect biodiversity and other ecosystem services (Manhaes et al., 2016). Furthermore, agricultural landscapes provide bundles of ecosystem services and land use choices that maximize the supply of one ecosystem service will not necessarily maximize the provision of other ecosystem service. Besides, the carbon storage capacity of plant biomass and soil is only one part of the overall carbon balance. In Paragominas, forest fires are an important factor for the total landscape carbon balance. Critically, the occurrence of fires is tightly linked to individual management decisions because, except from the Alto Rio Guamá Indigenous Reserve in the eastern part of the municipality, all major undisturbed forest areas in Paragominas are privately owned (i.e., Legal Reserves). Therefore, there is a need for developing effective forest fire prevention measures and farm management protocols in Paragominas to reduce the risk of forest fires.

We explored scenarios for a 15-year period, but it is necessary to go beyond this time horizon to understand what the effects of landscapes strategies are 25, 50 or even 100 years from now. This is critical for any prospects of developing carbon credit markets in the region. In this regard, agroforestry systems have the potential to foment restoration of secondary forest which can eventually evolve into diverse forests within longer time periods (De Jong, 2001; Blinn et al., 2013). Therefore, landscape scenarios such as the Hybrid mosaic have the potential to maintain the carbon storage gains beyond the 15-year period that we considered.

Finally, the InVEST model is a simplification of the carbon cycle and we relied on secondary data. For example, the model assumes that all LULC classes are in ‘equilibrium state’, at some fixed carbon storage level equal to the estimated soil carbon stocks for a given LULC type, and that the only changes in carbon storage over time are due to changes in LULC. Besides, the simulation output is only as detailed and reliable as the LULC classification and the carbon pool values obtained from secondary data. Our paper, however, is a first approximation to quantify the effects of different land use allocation strategies on carbon storage at the landscape scale in Paragominas for identifying possible land use policies at the landscape level. More research is needed to collect carbon data, including on-farm data, and validate our estimates of carbon stocks. Our study, nevertheless, provides a potential desirable endpoint (i.e., the Hybrid mosaic landscape) which can open discussions to identify farm pathways towards a multifunctional landscape.

5.5 Conclusions

The land sparing-land sharing debate has focused almost exclusively on biodiversity conservation, neglecting the implications of land use allocation on other ecosystem services. By focusing on carbon storage our study informs this discussion and points out implications of land structure and land use change on carbon storage in the municipality of Paragominas. Our results provide quantitative estimations on the carbon storage potential of a combined land sparing-land sharing approach (i.e., Hybrid mosaic scenario). In Paragominas, this hybrid strategy could translate into protecting large portions of primary forest from disturbances, allowing secondary forest regeneration, and implementing tree-based systems into the landscape matrix to increase carbon storage and establish biodiversity-friendly corridors that connect forest patches. On the other hand, our results suggest that strategies that consider agroforestry alone without secondary forest regeneration are less likely to increase carbon stocks at the municipal scale. Expansion of agriculture into forest would represent significant losses of aboveground biomass and soil carbon. In the context of the eastern Amazon region, the hybrid land use strategy can induce the implementation of heterogenous, tree-based production systems with higher carbon storage potential than the traditional monocultures and pastures of the region. The eight scenarios we presented in this paper show the effects of contrasting LULC strategies that may form the basis for enhancing multifunctional landscapes with a better potential to capture carbon in the eastern Amazon region.

5.6 Acknowledgments

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Chapter 6

General discussion

6.1 Introduction

Since the effective colonization of the Brazilian Amazon in the early 1970s, the region has followed a frontier trajectory in which a diversity of social actors and deforestation have shaped the construction of landscapes and territories. A consequence of these land use dynamics is that roughly one fifth of the Brazilian Amazon (720,000 km^2) has been deforested since then (INPE, 2017; Butler, 2018). Impacts of this forest loss include increasing surface temperatures, and declining biodiversity, evapotranspiration, precipitation, and carbon sequestration rates resulting in a general disruption of the local, regional, and global climate (Shukla et al., 1990; Werth and Avissar, 2002; Barlow et al., 2007; Salazar et al., 2007; Berenguer et al., 2014; Grace et al., 2014; Betts et al., 2017).

The Paragominas municipality in the eastern Amazon region, with a long history of logging and extensive cattle ranching, is one of the oldest forest frontiers currently transitioning towards land use intensification. This historical trajectory has shaped the landscape during the last six decades (Rodrigues et al., 2014) into a disconnected mosaic of regrowth and degraded forest, old agricultural fields, and pastures of low productivity (Nepstad et al., 1991). These land use dynamics in turn, have led to soil degradation, nutrients cycling disruption, biodiversity loss, changes in regional rainfall regimes and fire susceptibility (Uhl and Kauffman, 1990; Nepstad et al., 1999).

Given this context, this thesis explored the potentials of land use planning and land management to enhance landscape multifunctionality in the municipality of Paragominas. The objective of this thesis was to identify opportunities, trade-offs, and pathways to enhance landscape multifunctionality in terms of carbon storage, habitat for biodiversity and agricultural production through land use planning and land management. Specifically, I aimed:

1. To characterize and describe the landscape in terms of trade-offs between carbon storage, habitat for biodiversity and agricultural production of commodities (Chapter 2).
2. To understand farm diversity and its implications for agricultural intensification and diversification (Chapter 3).
3. To understand landholders' perceptions regarding forest conservation on private lands and its link with agricultural intensification (Chapter 4).
4. To explore the effects of landscape structure and land use change on carbon storage under contrasting land use and land cover scenarios (Chapter 5).

In Chapter 2, I provided a spatial diagnosis in terms of ecosystem services and their trade-offs across the landscape (Specific objective 1). This spatial diagnosis included carbon storage, habitat for biodiversity and commodity production. I selected these specific ecosystem services due to their intrinsic connection with the forest and the agricultural frontier. For this, I applied the conceptual framework of Functional Land Management (Schulte et al., 2014; Schulte et al., 2015; Coyle et al., 2016) which entails the notions of 1) supply of ecosystem services conditioned by biophysical factors and land uses, and 2) societal demands of ecosystem services embodied in environmental policies. This landscape analysis was based on a classification of the landscape into "landscape units" entailing land use and pedo-morphological combinations as indicated in the landscape matrix in Chapter 2. Based on this analysis, I identified 1) '*Natural areas'*, where the prevailing land use and land cover are primary forests that fulfil the demands for habitat for biodiversity and carbon storage, 2) '*Production areas'* where the demands for commodity production (i.e., soybean, beef, and wood products) are fulfilled in detriment of habitat for biodiversity and carbon storage, and 3)'*Sub-optimal areas*' where none of the three ecosystem services demands are fulfilled as these are areas mostly covered by degraded pastures and degraded forests.

In Chapter 3, I developed a farm typology based on farm structural characteristics that I collected through farm surveys to tackle the second specific objective of my thesis. I showed the diversity of agricultural intensification in Paragominas through the identification of three main farm types: 1) *Extensive cattle-soybean ranches*, 2) *Integrated farms*, and 3) *Soybean-based farms*. These three farm types suggested an agricultural intensification range (i.e., Extensive cattle-soybean ranches < Soybean-based farms < Integrated farms) where traditional cattle farms have been gradually converting fertile areas on clayey plateaus to soybean monocultures in the last twenty years (i.e., Extensive cattle-soybean ranches). Other younger farms have specialized and focused exclusively on soybean production since their inception (Soybean-based farms), and some other have made a leap towards temporal integration of crop and pastoral systems as it is the case for the wealthiest farms I encountered (Integrated farms). Extensive cattle-soybean ranches are the least intensified, followed by Soybean-based farms, whilst Integrated farms are the most intensified farming systems in Paragominas. A prime reason for such intensification process is land constriction after large-scale deforestation was controlled following the Green Municipality initiative in 2008, in conjunction with the modernization of the agricultural sector prompted by a soybean boom in Pará State in the early 2000s with the arrival of soybean producers from the states of Mato Grosso and Goiás (Brandão et al., 2005; Sauer, 2018). It is, however, not clear if a low-deforestation context in Paragominas will remain, given recent spikes of deforestation rates in the eastern Amazon region (Fonseca et al., 2020).

In Chapter 4, I aimed at understanding landholders' perceptions on the main policy tool in Brazil to protect forest and native vegetation in private lands i.e., the Legal Reserves (it mandates all farms in the Amazon to keep 80% of their area as forest conservation areas, in Paragominas this proportion can be reduced up to 50% in accordance with state policies). How does a landholder perceive that he/she cannot use up to 50-80% of his/her land for agricultural intensification in Paragominas? To investigate this controversial and disputed topic, I used Q methodology, a method developed in the field of psychology to assess subjectivity. I found three landholder types regarding their perceptions on Legal Reserves: 1) *Agribusiness-conservation coexistence enthusiasts*, acknowledged possible compatibility between Legal Reserves and agricultural intensification given a more flexible policy framework to relocate Legal Reserves and facilitate agricultural intensification, 2) *Policy complacent-market responders* showed a mix of indifference and relative complacency towards Legal Reserves while paying more attention to market demands, and 3) *Conservation-development antagonists* pointed out that taking care of the forest should not be their responsibility and perceived Legal Reserves as a burden and an obstacle for agricultural intensification. Diversity in perceptions was mainly driven by resource endowment and personal history which in turn conditioned landholding location and orientation production of the farm (i.e., livestock ranching or mechanized crop production). The findings of this chapter suggested that, when it comes to land use decision-making, landholders in Paragominas factor in forest and biodiversity conservation once they attain certain life standards. Otherwise, priorities are profits, production, and social status.

In Chapter 5, I used the landscape classification (i.e., landscape units) I developed in Chapter 2 to explore land use strategies under different anticipatory 2030 scenarios using the InVEST model (Sharp, 2020). These scenarios explored the implications of land use strategies in terms of carbon storage in aboveground biomass and in organic soil. The quantification of carbon storage for each scenario was based on secondary data obtained from the literature. Moreover, the scenarios ascribed to different "conservationist" or "productionist" visions and land use strategies, i.e., land sparing and land sharing. In this chapter, I showed the potential of combining land sparing and land sharing to introduce tree-based systems and support secondary forest succession to increase carbon storage at the municipal scale. The scenario analysis indicated the critical role of secondary forests to increase carbon storage across the landscape in abandoned fallows, whilst the sole implementation of agroforestry systems in alternatives scenarios was not sufficient to increase carbon storage compared to the 2015 baseline. Furthermore, in this chapter I described a possible policy mechanism that could trigger coordinated land use management across farm boundaries towards landscape management and common landscape objectives (e.g., increase carbon storage, landscape multifunctionality). In this regard, incentives and mechanisms based on game theory, (Parkhurst et al., 2002; Parkhurst and Shogren, 2007; Banerjee et al., 2017; Panchalingam et al., 2019), such as the one suggested in Chapter 5, have the potential to enable cooperation among landholders. Otherwise, current intensification schemes based on agro-industrial agriculture are likely to prevail. This is problematic in terms of soil and forest-based ecosystem services as such development can easily drive mechanized agriculture into remnants of undisturbed forests as shown in recent studies across the region.

By identifying the diversity of trade-off areas (Chapter 2), farms (Chapter 3), and forest conservation perceptions (Chapter 4), I could derive that in ‘Production areas’ identified in Chapter 2, most of the farm types are young ‘Soybean-based farms’, mostly run by ‘Conservation-development antagonists’ who do not have Legal Reserves on their farms and view conservation as a burden, whilst they ought to rent land both for production and conservation. Another narrative is that in ‘Suboptimal areas’, ‘Extensive-soybean-cattle ranches’ are predominant and run by ‘Policy complacent-market responders’ who do not necessarily pursue policy changes as the extensive model that allowed them wealth acquisition in the past, is still profitable due to the size of their landholdings. Therefore, these landholders can intensify some areas, while conserving the ‘fazendeiro’ identity and culture forged during the colonization phase. Finally, a third narrative is that ‘Nature areas’ are mostly populated by large ‘Soybean-based farms’ and ‘Integrated farms’ with large Legal Reserves in the hands of agribusiness firms who comply with the environmental legislation, as they have enough resources to intensify in distant areas and to implement integrated agro-pastoral systems. These farms are primarily run by ‘Coexistence agribusiness-conservation enthusiasts’ with the most “progressive” perceptions.

This 1:1:1 relation between trade-off area, farmer type and perceptions is useful to understand the socio-ecological system of Paragominas. However, the links can be more fluid, and therefore these narratives should be used with caution and only as a general pattern to understand the Paragominas frontier. These narratives should be interpreted as basic preconditions in terms of the land system, ecosystem services trade-offs, and social actors to elicit dialogues towards project-planning capacity and common goals at the municipal level. In this regard, Chapter 5 presents an illustration of what a common objective could be (i.e., the ‘Hybrid mosaic landscape’) to facilitate novel dialogues on land use planning and landscape management in Paragominas.

6.2 Territorial intelligence and certification in Paragominas: multi-actor collaboration to foster transition pathways

The overarching objective of this thesis was to analyze the heterogeneity of biophysical conditions, farm systems and landholders to inform decision-making towards desired landscape outcomes. Therefore, the results of this thesis can be placed within the socio-technical and political decision-making process currently taking place in Paragominas elucidating such desired outcomes.

After Paragominas left the Federal Government blacklist of highest deforesters in 2010 following the Green Municipality initiative, municipal goals shifted from ending deforestation towards land use suitability and jurisdictional certification as a strategy to obtain funding and market incentives (Brandão et al., 2020). In 2019, the municipality of Paragominas launched the Intelligence and Development Territorial Plan (IDTP) (Plano De Inteligência e Desenvolvimento Territorial de Paragominas, Decreto municipal 316/2019) involving several national and international research institutes, universities, the local farmer union, and the Municipal Government. The Territorial Intelligence plan aims at sustainable development and landscape multifunctionality focusing on land use reorganization and reconnection of the forest matrix to increase forest ecosystem services in Paragominas (Brandão et al., 2020). The plan contemplates four strategies[7] including 1) land use planning for ecosystem services, 2) life quality of rural communities, 3) agricultural intensification, and 4) territorial certification (Prefeitura Municipal do Paragominas, 2019). It is early to assess the effectiveness of this plan but adopting territorial intelligence as a central concept suggests a novel approach in the region officialized by municipal policies.

[7] To operationalize these strategies the IDTP contemplates seven actions: i) developing landscape zoning policies, ii) developing a territorial intelligence municipal system, iii) developing credit tools, iv) training institutional actors on agricultural intensification and diversification, v) establishing private-public partnerships, vi) developing a territorial development board, and vii) developing a communication program for spreading information on territorial development (Prefeitura Municipal do Paragominas, 2019).

Territorial intelligence is defined in the literature as an information and anthropological process initiated by local actors aiming at appropriating land resources by mobilizing and transforming the "energy" of a territory into project capacity (Bertacchini et al., 2013). This implies attitudinal changes by the local population to adopt the logics of a shared project with endogenous values, codes, rules, interaction, knowledge and information channels (Bertacchini, 2012; Bertacchini et al., 2013). In this sense, territorial intelligence can be conceived as what Jasanoff (2004) calls a process of knowledge "coproduction" where ideologies and imaginaries (e.g., the frontier, fazendeiro, modernization, development, etc.) have an important role in the process of coproducing science and technology. This is particularly important in the case of land use models and maps that encompass a strong imaginative component to harness transformation and effective land use planning (Soares-Filho et al., 2004; Hecht and Rajão, 2020).

Within a process of territorial intelligence in Paragominas, the results of my thesis (i.e., spatially explicit information and typology tools) can inform processes of mediation and interaction between social actors for iterative land use and spatial planning, i.e., Socio-Technical Information and Communication Arrangements (STICA) (Bertacchini et al., 2013). STICA can be classified into six major categories (i.e., analytical, creative, cognitive, relational, decision-making choosing and operational) (Bertacchini et al., 2013) and the results of this thesis can contribute to the 1) analytical, 2) creative, 3) cognitive, and 4) relational functions. The results from Chapter 2 for example, have a spatially explicit analytical function to understand the biophysical complexity; results from Chapters 3 and 4, typified farming systems and diversity of perceptions possibly fulfilling a relational function; results of Chapter 5, have a creative function to conceive land use and land cover scenarios that seem currently implausible but that could be desirable for landscape multifunctionality. Ultimately my thesis, had the objective to fulfil a cognitive function by simplifying the complexity of the Paragominas socio-ecological system and enable its management from a territorial approach within a dynamic regional and global context (i.e., decision-making, and operational functions performed by the relevant social actors). Therefore, the results of this thesis can inform strategies and actions pertaining to forest conservation, agricultural intensification, and diversification as contemplated by the IDTP (Table 6.1).

Table 6.1 Functionalities of Socio-Technical Information and Communication Arrangements (STICA) and links with the chapters of this thesis.

Functions of STICA	Definition	Outcome and chapter of this thesis	Links between this thesis results and STICA formation.
1) Analytical	• Representing and understanding territorial complexity. • Detecting a problem situation and its spatial extent.	A spatial diagnose of the landscape in terms of ecosystem services trade-offs (Chapter 2).	In Chapter 2, I spatially assessed biophysical supply and policy demands for carbon storage, habitat for biodiversity and commodity production in Paragominas. These results led to the identification of areas of potential trade-offs between ecosystem services at the municipal scale.
2) Relational	• Identifying stakeholders. • Developing awareness of diversity of mental representations. • Legitimizing institutional actors. • Engaging and legitimizing local actors. • Generating openness between social groups. • Creating a community.	A typology of rural landholdings (farming systems) (Chapter 3). A typology on landholders' perceptions (Chapters 4).	In Chapter 3, I typified farming systems to enable mental representations of farms in the landscape. In Chapter 4, I identified different landholders in terms of their perceptions towards Legal Reserve to potentially enable engagement and openness between social groups to have a dialogue on a contemptuous topic (i.e., forest conservation in private properties).

3) Creative	• Imagining the future of the territory. • Building up scenarios. • Imagining innovative solutions.	Anticipatory landscape scenarios (Chapter 5).	The aim of these scenarios generated in Chapter 5, aimed at imagining innovative landscape designs with the potential to enhance carbon storage in Paragominas. Specifically, the 'Hybrid landscape' model presented in Chapter 5, combined land sharing and land sparing strategies to imagine a future in Paragominas where forest-based like systems are implemented at scale, while secondary forests are maintained for regeneration and primary forests are protected from disturbances.
4) Cognitive	• Providing shared spatial background data. • Accessing mental representations. • Expressing and articulating multiple relations to the world. • Reframing perspectives. • Developing awareness. • Accessing available information. • Ensuring collective memory, visualizing, exploring, explaining the available information. • Simplifying the territorial complexity. • Creating an epistemic community.	All chapters.	The aim of this thesis is to advance knowledge on the socio-ecological system of Paragominas, i.e., to make sense out of the heterogeneity of ecological conditions (trade-offs), farming systems, perceptions, and implications of land use changes. Chapter 6 aims at articulating these multiple relations towards envisioning landscape multifunctionality.

It is important to notice the terminology used within a territorial intelligence framework i.e., territory, as opposed to landscape. The Portuguese terms *paisagem* (landscape) and *territorio* (territory) differ in their connotations in an Amazonian context, as the latter conveys a spatial dimension with a heavy load of political, juridical, economic, and cultural content. Beyond idiomatic differences however, ontologically, the landscape focuses on natural factors, while the territory does it on social factors; epistemologically thus, landscape aims at understanding the system in question (i.e., the objective of this thesis) while the territory implies governance, ownership and rights over land and resources (McCall, 2016). Along the chapters of this thesis, I used the term "landscape" as an analytical, neutral unit that allowed me to conduct this study from a landscape ecology perspective. However, territory, as a political term, aims at shifting power decision away from global and national actors towards local actors (McCall, 2016), and it is precisely this process that my thesis aims to inform.

In theory, by managing 1) *physical factors* (resources and energy), 2) *logical flows*, (information and representations of the territory), and 3) *identity factors* (symbols and social norms) a territory can become an autonomous, self-organizing, self-analyzing and self-monitoring system driven by a networking process capable to collectively administer resources and resolve conflicts (Bertacchini et al., 2013). Because municipalities in the Amazon region have played a key role in the implementation of federal and state policy and governance measures in the last two decades (Thaler et al., 2019), the municipality of Paragominas encompasses both the landscape and the territorial dimensions.

A second important strategy of the IDTP is territorial certification of the municipality based on a jurisdictional approach. The latter is a landscape-based governance scheme that emphasizes on the political sub-national levels at which land use decisions are enforced to reduce deforestation (Fishman et al., 2017). In Paragominas, municipal institutions have been adopting this approach to guide land use dynamics and address structural drivers of deforestation through monitoring and enforcement capacity, while tackling the heretofore insufficient private sector involvement and market incentives to promote socioeconomic changes at local level (Brandão et al., 2020).

In 2019, Paragominas achieved the Verified Sourcing Area (VSA) status granted by the Sustainable Trade Initiative (IDH), an organization based in Utrecht, the Netherlands, and supported by several European governments and international foundations (www.idhsustainabletrade.com). The VSA status encompasses a pact between private and public institutions to achieve sustainability targets and together with jurisdictional approaches, are among the newest multilayer environmental governance schemes for landscape-based approaches to govern agricultural supply chains (Diaz-Chavez and van Dam, 2020). These frameworks are increasingly gaining interest among traders who seek to secure the supply of zero-deforestation commodities (Wolosin, 2016).

Jurisdictional approaches have emerged from the recognition that local governance focusing on stopping deforestation through global certification processes without inclusive participation of local governments have achieved as much as they can (Meyer and Lujan, 2017). The state of Mato Grosso for example, has structured various jurisdictional instruments in the last decade to address deforestation and forest degradation by reducing the environmental impacts of soybean production and cattle ranching in various municipalities (IDH, 2018; Diaz-Chavez and van Dam, 2020). Nevertheless, the scope of these agreements under landscape certification schemes have shown limited opportunities for paradigm shifts, appearing more as reproductions of sectorial rationales prioritizing private interests, and risking to become mere "greenwashing" mechanisms (Milhorance and Bursztyn, 2018). Critics of these environmental governance mechanisms in the Amazon argue that these have served the purpose to "re-territorialize" the region enabling the advancement of so-called industrial neo-extractivism through the introduction of the soybean industry (Baletti, 2012; 2014). That is, environmental governance as a process originally oriented towards sustainable development has turned into a set of projects advancing a corporate agenda. For example, it has been argued that the Responsible Soybean Initiative and the Soybean Moratorium implemented to mitigate the effects of soybean expansion in the state of Pará have had questionable environmental benefits, but on the other hand, have reinforced the hegemony of multinational players and destabilized social local movements (Baletti, 2014). Baletti (2014) argues that technocratic approaches taken by such governance mechanisms tend to ignore historical contexts and thus neutralize political attempts for alternative non-commodification initiatives, ultimately ignoring the ethic-political factors revolving around competing visions for the Amazon (e.g., the folk frontier versus the official-neoliberal frontier).

This outcome could also be the case in Paragominas if certification mechanisms at the municipal level are not modulated by a genuine territorial process in which objectives and monitoring mechanisms are not clearly defined. It will be interesting to see how the processes of landscape certification and territorial intelligence unfold in parallel as the latter is by definition an endogenous process, while landscape certification mechanisms seem to take shape at higher domains than the local territory. The Brazilian Amazon has a long history of ambivalence and contradictory policies (Arvor et al., 2016) and it would be desirable that a territorial process avoids the exacerbation of such contradictions in Paragominas.

A territorialization process in Paragominas should question current models of agricultural intensification based on industrial agriculture and commodity production. Instead, models of agricultural intensification based on ecological principles that rely on ecological processes and regulation, rather than on input-based technologies, appear as a more sound strategy to attain multifunctionality (Tittonell, 2014). In this regard, in Chapter 2, I showed the prevalence of trade-offs between agricultural production and forest conservation as characteristics of current agricultural intensification patterns based on industrial agricultural practices and a legacy of extensive cattle ranching. In Chapter 5 on the other hand, I showed that agroforestry systems and secondary forest regeneration can introduce more biodiverse systems able to capture more carbon towards sustainable food systems. Ultimately, the main objective of a territorial intelligence process is to forge citizenship, democracy, social equity and social and economic development within the relevant spatial scale to safeguard its natural capital (Bertacchini, 2012).

6.3 From a land sparing grand design to a “territorialized” landscape in Paragominas?

As in most parts of the Brazilian Amazon, the predominant pathways for agricultural intensification during the last twenty years in Paragominas have revolved around the intensification of cattle ranching via improved pasture management and a transition from cattle ranching to industrial soybean monocultures following a land sparing[8] logic (Thaler, 2017). A third pathway that has received less attention is agricultural diversification through agroforestry systems and land sharing approaches, which have been discussed in the region almost exclusively in the context of family agriculture (Arnauld de Sartre et al., 2016).

In this regard, the ‘Hybrid mosaic’ landscape anticipatory scenario I presented in Chapter 5, depicts a pathway beyond the dominant land sparing format to foster further research that

[8] The land sparing model can be traced back to the Borlaug hypothesis, which poses that agricultural yield increases following the Green Revolution saved millions of hectares for wildlife-nature conservation around the world (Angelsen and Kaimowitz, 2001a). The Jevons’ paradox, however, observes that efficiency gains go often hand in hand with expanded market demands triggering further expansion of agriculture into wildlife areas, i.e., the so-called “rebound effect”. The land sharing model on the other hand, aims at integrating biodiversity conservation and agricultural production on the same land by using less intense, wildlife-friendly agriculture (Phalan et al., 2011b).

informs governance processes aiming at landscape multifunctionality through land sharing configurations at the municipal level. The current Paragominas landscape structure already facilitates a hybrid land sparing-land sharing mosaic because undisturbed forests are located in the extremities of the municipality (i.e., large Legal Reserves on the west side and the Guamá Indigenous Reserve on the east side of the municipality), pastures and intensive agriculture concentrates in the central axis, close to the paved road (i.e., BR-010 federal highway) (i.e., land sparing pattern), while in between, land sharing forest-based systems could recolonize degraded soils and restore forest cover. Thus, a hybrid mosaic scenario depicts a possible transition in Paragominas from a municipal land sparing configuration to a more diversified model based on tree-based systems and regenerating secondary forests, intermingled with monocultures, productive pastures, and undisturbed primary forests.

The prevalent land sparing logic in the eastern Brazilian Amazon is tightly linked with the development and modernization narratives advanced by the agribusiness lobby reflected in the perceptions that I captured in Chapter 4. The perceptions of '*Conservation-development antagonists'* for instance, seemed to be shaped by the most extremist faction of the agribusiness narratives in which industrial agriculture has an absolute, legitimate priority over forest conservation in order to guarantee rural development. Kröger (2017) coins the term "brown economy" to refer to this ideology portraying forests as an obstacle to global food security and Brazil's modernization and consolidation as the prime global commodity powerhouse. '*Agribusiness-nature coexistence enthusiasts'* and '*Policy complacent-market responders'* on the other hand, seemed to hold more flexible views within the agribusiness spectrum in which agriculture and nature can coexist in the landscape, given a spatial separation from each other and a more flexible policy framework. Arguably, these landholders follow a "green capitalism" ideology understood as a normative frame that conceives capitalism as the only realistic way to ensure the protection of nature via commodification of natural resources and internalization of externalities (Kröger, 2017).

In the Brazilian Amazon, a land sparing logic prevails not only because of the agribusiness sector, but because an array of other influential actors (e.g., federal and state institutions, NGOs and international corporations) assemble into a governance system advancing a land sparing grand design for the Amazon region, i.e., a so-called *land sparing complex* (Thaler, 2017). The reduced deforestation during the 2004-2012 period in the Amazon was the result of a governance process (i.e., supply chain interventions, expansion of conservation and indigenous reserves, enforcement of command-and-control policies) promoted by the land sparing complex pursuing regional economic development transitioning from an "extractivist" (characteristic of the colonization phase that depleted local resources) to a "productivist" economy founded on agro-industrial intensification, environmental compliance, and induced land scarcity through the creation of large protected areas (Thaler, 2017). Other contingent factors such as low commodity prices in the international market also played an important role in curbing deforestation in the Amazon during that period (Fearnside, 2017a).

While at the national level, conservation legislation enforcement targeted industries and supply commodity chains to halt deforestation, at the municipal level, governance initiatives replicated the "land sparing complex" by halting large scale deforestation and promoting agricultural intensification in open available areas (Thaler et al., 2019). In Paragominas, this is exemplified by the Green Municipality initiative, that brought together the municipal government and rural elites to agree on a zero-deforestation pact, and on geo-referencing all private properties under the Environmental Rural Registry (CAR for its Portuguese acronym) (Viana et al., 2016). The Green Municipality initiative was framed as a process of "ecological modernization", where several social actors were mobilized to stop large-scale deforestation and incur in a process of technological modernization for agricultural intensification in medium and large rural landholdings (Carneiro and de Assis, 2015).

These developments however, ought to be understood as a dual project of environmental governance to combat large-scale deforestation but also as a process of territorialization through agricultural intensification forged by the land sparing complex (Thaler et al., 2019). This acknowledgment will be crucial for the territorial intelligence process in Paragominas to question whether a land sparing, agro-industrial model is desirable to keep on replicating. The re-politicization of the landscape concerning its landscape structure (i.e., land sparing or land sharing) should be a debate about imaginaries of the human-nature relationship. The land sparing approach has been dominant not because it has proven higher sustainability but rather because its assessment relies on more simple metrics than land sharing approaches which require a more holistic perspective including both human and environmental systems (Loconto et al., 2020).

The latter points out the importance of collaboration among local stakeholders within a territorial intelligence process in which landholders are not merely users of resources but also potential experts (Bertacchini, 2012; Bertacchini et al., 2013). The 'Hybrid mosaic' landscape I proposed in Chapter 5 is in tune with such philosophy of multi-stakeholder collaboration as its operationalization would require coordinated land planning and cooperative land use management across farm boundaries. This implies that, to go beyond the current land sparing complex in Paragominas, a re-politicization of the frontier is needed as a territory that is shaped by an endogenous governance process rather than by external drivers. Whether that leads to a hybrid landscape structure is up to local stakeholders within a process of territorial intelligence.

6.4 An adaptive mosaic to attain landscape multifunctionality in Paragominas

Since the early 2000s, the intensification process in Paragominas, has prompted land use dynamics dominated by mechanized soybean monocultures replacing pastures and expanding into clayey plateaus (Poccard-Chapuis et al., in preparation). In terms of forest coverage, this landscape transition is having two contrasting effects: on the one hand, contrary to the land sparing hypothesis, the expansion of soybean is putting pressure on primary forests located on the fertile plateaus, while on the other hand it is freeing up areas that are not mechanizable and abandoned to secondary forest succession (Poccard-Chapuis et al., in preparation). Therefore, the use of land and its influence on ecological functioning in Paragominas is currently characterized by a potential rebound effect (Alcott, 2005) and a forest transition (Mather, 1992). These two processes are distributed across the landscape according to the different land use and pedo-morphological combinations I described in Chapter 2.

The land use dynamics described above suggest that the municipality of Paragominas lies at a crossroad between following a post-forest frontier path, where rural development is decoupled from deforestation, or gearing towards a frontier landscape where agricultural expansion into primary forest resurges. This observation is consistent with my results from Chapter 2 where I identified areas of potential suboptimal use due to forest degradation and pasture abandonment, and pointed out the risk of croplands (i.e., Production areas) expanding into forest areas of clayey plateaus where the supply of carbon storage and habitat for biodiversity is the highest (i.e., Nature areas). The results of Chapter 3 aligned with these results at the farm level, as traditional cattle ranches are increasingly growing soybean in mechanizable areas (i.e., clayey plateaus), while the emergence of soybean-based farms corresponds to the transformation of former cattle ranches into monoculture farms that were prompted by the soybean boom of the early 2000s in the whole eastern Amazon region (Schielein and Börner, 2018).

In practice, gearing towards a post-forest frontier in Paragominas and producing different goods and ecosystem services on the same land (i.e., land use diversification to increase landscape multifunctionality), may imply the intensification of some land uses and the dis-intensification of others (Meyfroidt, 2018). To accomplish this process a model of an “adapting mosaic” can be a pertinent pathway to design local-ecosystem-based management strategies and local institutions that invest in human and social capital to improve knowledge on ecosystem functioning (MEA, 2005). An “adapting mosaic” is managed as a system, as opposed to the independent management of each cell of the mosaic meeting purely sectoral ends (Sayer et al., 2013). This sectorial management style currently enforced in Paragominas by the land sparing paradigm could lead to the further “artificialization” of the Paragominas landscape (Poccard-Chapuis et al., 2015). The hybrid landscape I presented in Chapter 5 has been conceived as an adapting mosaic, which fits within a process of territorial intelligence and jurisdictional approaches where endogenous governance is enforced.

Considering the “land sparing-brownish-green economy” rationale that prevails in Paragominas, a “hybrid landscape-forest economy” model to pursue more heterogenous landscapes and more diversified food production could be an adaptation and mitigation pathway relevant to Paragominas. The ‘Hybrid mosaic’ landscape presented in Chapter 5 advances agroforestry systems and secondary forest succession as prominent elements in the landscape to forge a forest-based local economy. Therefore, a territorial intelligence process, to which the results of this thesis can contribute regarding the formation of STICA (Table 6.1), should be oriented towards integrating land sparing and land sharing approaches as the one I proposed in Chapter 5 (Hybrid landscape) to increase the possibilities of accomplishing landscape multifunctionality and a more inclusive territorial project. Otherwise, the risks for environmental governance turning into a greenwashing mechanism could be proven right in Paragominas. Moreover, command-and-control measures do not seem sustainable in the long term to keep low deforestation rates in the region.

The farm typology presented in Chapter 3, can be indicative of which intensification pathways can be more relevant for each farm type, but it does not imply that a pathway is exclusive for a specific farm type. In the end, this will depend on the farmer’s decision and to the extent that biophysical characteristics of the landscape and land cover are used as intensification criteria (Figure 6.1). Implementing such intensification/diversification pathways, however, would require sectorial collaboration to access data on biophysical conditions as well as on forest quality to develop individual protocols at the farm level that comply with the complex policy framework that applies in the Brazilian Amazon. Moreover, policy instruments such as incentives and payment for ecosystem services (PES) could also support farm intensification/diversification pathways.

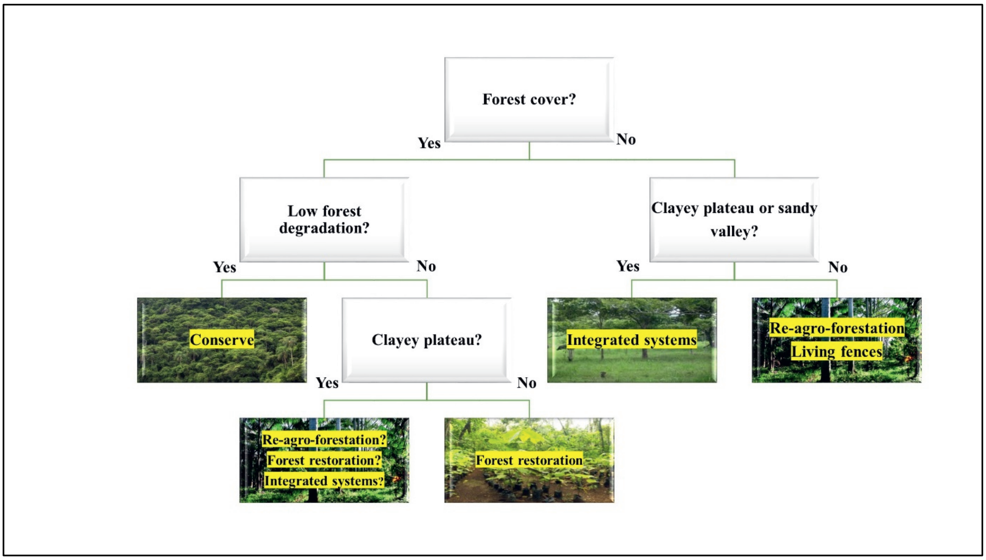

Figure 6.1 Decision tree based on forest cover and pedo-morphology criteria for agricultural intensification and diversification to enhance landscape multifunctionality in Paragominas. Forests with low levels of degradation should be all conserved; degraded forests could be subject to forest restoration or conversion to productive diversified systems. In open areas suitable for intensification (i.e., clayey plateaus or sandy valleys), implementation of integrated agro-silvo-pastoral system can be pertinent; while in marginal areas less intensive systems can be implemented (e.g., living fences). Pictures taken from Porro et al. (2012); Pezo et al. (2018); Helmholtz Association (2019), and Yale School of the Environment (2020).

6.5 Muddling through towards new visions and values in Paragominas?

An adaptive mosaic relies on incrementalism as a policy and decision-making approach to address deforestation and environmental problems, i.e., so-called a "muddling through" approach (Sayer et al., 2008; Sayer et al., 2013). This term firstly coined by Lindblom (1959) refers to the long-term engagement of stakeholders aiming at incremental and gradual policy changes under an evolutionary premise as opposed to a revolutionary one. If structural changes are to happen in Paragominas concerning agricultural intensification and forest conservation, a gradual evolutionary pace appear more feasible than an abrupt regime change. A structured approach to muddling through can define the logics on how to instigate a desired change within a system over a specific period (Sayer et al., 2008). Such "disjointed incrementalism" entails a gradual, flexible, integrative and adaptive course of action rather than a long-term strategy focused on optimum solutions (Lindblom, 1959; 1979). In complex decision-making contexts where uncertainty is present, a dynamic and structured strategy of "muddling through" can be more successful than a strategy of anticipation (von Detten, 2011).

An uncomfortable recognition concerning environmental policy decisions, and particularly relevant in frontier contexts, is that most people deem material wealth as more important than harmony with nature (Sayer et al., 2008), an observation consistent with my results from Chapter 4. Therefore, proposing landscape grand designs for the region is futile. Rather, landscapes and territories must be understood as integrative constructs that include human institutional, aesthetic, and economic attributes generating pathways from within, and informed by scientific endeavors (Sayer et al., 2008; Sayer et al., 2013). In this regard, strategies to facilitate a process of muddling through include engaging in scenario construction to explore possible futures and game-based approaches to establish constructive dialogues (Garcia et al., 2020).

In the last two decades, the logic behind land sparing has been picked up by the industrial agricultural sector as a strategy to promote its practices (Loconto et al., 2020), while on the other hand, land sharing, low-input agriculture is associated with smallholders in developing countries with limited access to external inputs (Tscharntke et al., 2012). At its core, nevertheless, the land sparing-land sharing debate represents two contrasting visions on the human-nature relationship: on the one hand, nature and agriculture cannot cohabite because they have opposing needs, while on the other hand, biodiversity and agriculture are interdependent and part of the same system (Loconto et al., 2020).

In this regard, the ‘Hybrid mosaic’ landscape (Chapter 5) is in line with the idea of integrative agricultural landscape management to create win-win-win situations between environmental, societal and economic benefits (Foley et al., 2005). Although large-scale agroforestry competing with soybean monocultures or pastures seems a distant possibility in Paragominas, there are certain local conditions that indicate changes in “visions” for the landscape may be possible in the mid-term. Landholders in Paragominas tend to stay and live in the municipality, different from larger landholders from the state of Mato Grosso for example, many of whom reside in São Paulo or other large cities. Thus, landholders of Paragominas remain “local” within the territory and so they are affected first-hand by environmental problems affecting life quality. For example, glyphosate and other pesticides, human exposure to which is increasingly linked to cancer risk (Zhang et al., 2019), are widespread inputs in cattle ranches and soybean farms across the region. Smoke from forest fires resulting from extended dry seasons and forest degradation, has also been affecting the health of the local population (UOL, 2015; Globo, 2016). Moreover, diversified systems producing locally consumed food can promote more balanced diets. It is interesting to observe for instance, the popularity of vegetarian restaurants in Paragominas city that are visited daily by soybean and meat producers.

Understanding how environmental changes produce feedbacks on societal and individual behavior is critical to enable transitions as an endogenous self-organization process within a socio-ecological system (Lambin and Meyfroidt, 2010). The effects of this feedbacks on human behavior in turn, are shaped by cognitive processes of perception, interpretation, and evaluation of environmental changes (Meyfroidt, 2013). These processes are underlaid by beliefs, values and emotions linked to sense of place, identity, and connectedness with nature and other people (Figure 6.2) (Meyfroidt, 2013). Therefore, motivations behind land use decisions reflect values while self-reflection provides the cognitive bases for learning and adapting such values driving decision making. In this sense, a territorial intelligence process can provide a self-reflection platform to advance policies that encourage endogenous socio-ecological feedbacks supporting cognitive processes of perceptions, interpretations, and evaluation of environmental changes. Local policies should not only focus on monetary incentives, and market interventions but also acknowledge motivations and the underlying beliefs and values that lead to metacognitive capabilities at the individual and collective level regarding land management. Scientific theories largely assume the rational actor expected to maximize utility as the basis to understand human behavior but diversity of subjective motivations, cognitive processes, and social networks play a determinant role when it comes to environmental change and land use decisions (Meyfroidt, 2013).

Thus, science can assist in this endeavor, but it will be on the hand of the social actors in Paragominas to decide on the direction that their territory takes. This should be a process of communal decision operationalizing a "muddling through" approach through a territorial intelligence development. This process should steer "intelligent decisions" able to specify available knowledge, focus on uncertainty, perceive and reassess current developments, find consensus and anticipate future dissent (von Detten, 2011).

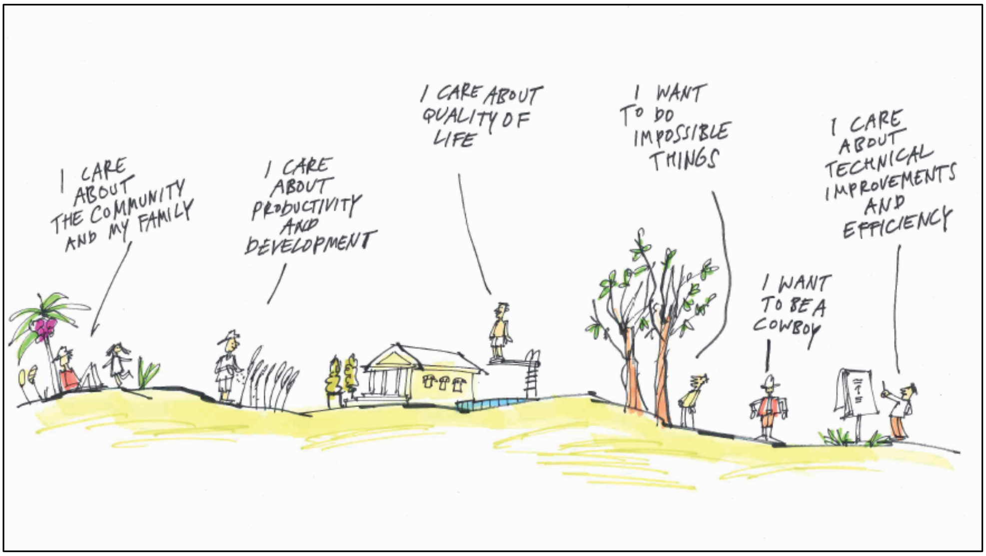

Figure 6.2 Heterogeneity of values among farmers and landholders in Paragominas captured during field visits in 2016 and discussed during the Farming Systems Ecology group vision-week workshop in August 2017. Drawing by Geert Gratama.

6.6 Landscape ecology and land system science: transdisciplinarity to analyze landscape complexity and heterogeneity

The work I developed in this thesis was initially conducted from a theoretical landscape ecology perspective, i.e., the study of spatial patterns and interactions within ecosystems driving ecological processes (Clark, 2010). As I advanced in my research, I found myself increasingly incurring into other fields to finally adopt an integrated approach in which land system and land change science became fundamental. Land system science studies the past, current, and projected state of terrestrial systems emphasizing on the processes and activities related to the human use of the land (i.e., socioeconomic, technological, and organizational dimensions) in a context of continuing global environmental change (Verburg et al., 2013; Verburg et al., 2015). It operates from an interdisciplinary approach between social and natural sciences to offer mitigation and adaptation options to global environmental change in land use and land cover mosaics (Verburg et al., 2013).

Since the 1990s, land system science has focused on the monitoring and modelling of ecological impacts of changes in land use and land cover, but it has been increasingly shifted towards integrative research studying drivers and impacts of changes in socio-ecological systems at different scales, i.e., land change science (Verburg et al., 2013). This implies studying the relationship between 1) *peopl*e, 2) (spatial) *patterns* and 3) (socio-ecological) *processes*, which demands transdisciplinary approaches involving land system architecture, landscape ecology, land system science, political ecology, and related fields (Frazier et al., 2019; Roy Chowdhury and Turner, 2019). In this thesis, I worked primarily between the realms of landscape ecology and land change science (Table 6.2) to study *landscape patterns* in terms of ecosystem services trade-offs (Chapter 2), the *socio-ecological processes* of agricultural intensification (Chapter 3), and *people's perceptions* on forest conservation (Chapter 4). In turn, this served the purpose to generate different scenarios of land use that I assessed in terms of carbon storage as a first step to elucidate pathways for landscape multifunctionality (Chapter 5) (i.e., mitigation and adaptation measures to global changes).

Table 6.2 A transdisciplinary approach between landscape ecology and land change science to study the socio-ecological system of Paragominas.

Characteristics of the field	**Landscape ecology**		**Land change science**
Main epistemological focus	Ecological processes ⇄	**Spatial patterns in the environment**	⇄ Social processes
Roots	Traditional ecology		Land system sciences
Focus	Landscape and land use planning		Human dimensions of landscape heterogeneity
Trend	Increasingly focusing on the role of human processes i.e., culture		Studies and advocates for a stronger role of decision making in shaping spatial patterns of the landscape

* Based on Frazier et al. (2019)

Within the realm of land change science, the concept of "land system architecture" is defined as the composition and spatial structure of land units across a particular area where different land covers and land uses confluence, linking spatial dimensions of landscape ecology and human activities (Turner et al., 2013). Therefore, the architecture of land systems is a prime determinant of ecosystem functions and land's capacity to provide ecosystem services (Turner et al., 2013). I applied, the term "landscape structure"(Klingbeil and Willig, 2009) (Chapters 2 and 5) from a landscape ecology perspective referring precisely to the architecture of the land system in Paragominas. In this sense, a fundamental assumption of my thesis was the design of land system architecture or landscape structure, as a strategy to minimize trade-offs between ecosystem services, and identifying adaptation and mitigation strategies (i.e., diversification pathways).

Furthermore, the rationale of land change science aligns with the conceptual framework of Functional Land Management (Schulte et al., 2014; Schulte et al., 2015) (FLM) that I applied in Chapter 2 in so far that both attempt for the optimization of ecosystem services from a spatial perspective, i.e., the allocation of land uses according to biophysical characteristics (what is this soil particularly good at?). Therefore, the results I presented in Chapter 2 integrated elements of land change science to derive a map of the land system architecture in terms of trade-offs between soil-based ecosystem services. Chapters 3 and 4 focused on farming systems, and landholder perceptions on Legal Reserves (i.e., private forest reserves) respectively, which allowed me to account how local land use decisions are influenced by external drivers i.e., globalized markets and federal policies. Interconnectedness between socio-ecological systems at different scales is of central interest in land system science as it conceptualizes land as a globalized good (Lambin and Meyfroidt, 2011). For instance, land availability mediates agricultural expansion and the likelihoods that land use is displaced to distant places; property rights and land tenure security can also influence land use displacement (Meyfroidt et al., 2014). Reduced deforestation in the Amazon region during the 2004-2012 period came at the cost of increasing deforestation in the Cerrado due to spill-over effects (Dou et al., 2018). In prior decades, sugarcane expansion in the state of São Paulo displacing cattle ranching elicited forest conversion in the Amazon region (Andrade de Sá et al., 2013). Thus, identifying these links and indirect effects of land use change (i.e., tele-coupling) is of critical importance when considering and assessing land use planning and conservation to analyze interaction between distant systems (Dou et al., 2018).

This high interconnectedness between socio-ecological systems in the current global context confronts us with an epistemological challenge to address complex systems that exceeds our conceptualization abilities (Dougherty, 2016). In land system science, a promising transdisciplinary direction to cope with such complexity is the development of contextual generalizations exposing causal explanations of observable phenomena, so-called "middle-range theories" (Meyfroidt et al., 2018). These aim at describing causal mechanisms and effects

(Meyfroidt, 2016) while balancing generality and precision, as opposed to high-level unified theories, or case studies relevant only to place-based specificity (Meyfroidt, 2018). For example, at the interplay between land change science and landscape ecology (the approach applied in this thesis), lays the understanding of landscape patterns, structures (i.e., causal effects), and functions across macro and micro-level ecological interactions (i.e., causal mechanisms) (Wu, 2013).

Regarding the modelling of complex socio-ecological systems, there are four possible options:1) disregarding modelling complex systems that cannot be validated, 2) modelling complex systems and pretend they are validated, 3) modelling complex systems, acknowledging that the models are not validated, utilizing them pragmatically where possible, but being extremely cautious about its interpretation, and 4) striving to develop new knowledge (Dougherty, 2016). The position I took concerning the results of my thesis is option 3: I acknowledged throughout my chapters that my results captured patterns that may hold for validation (i.e., causal mechanisms), but did not claim they captured the entire complexity of the socio-ecological system in Paragominas. At the same time however, by stepping outside of the landscape ecology domain towards land use change science, my thesis strived towards transdisciplinary information regarding biophysical, farming, and subjective heterogeneity (Figure 6.3). Thus, pursing option 3, may be a pathway towards sound multilevel epistemology that supports scientific theories at different levels of validation (option 4) (Dougherty, 2016). This is critical because tackling and solving anthropogenic climate change and environmental global crises, will increasingly demand from science, to be faster at assembling integrated, holistic, yet precise knowledge.

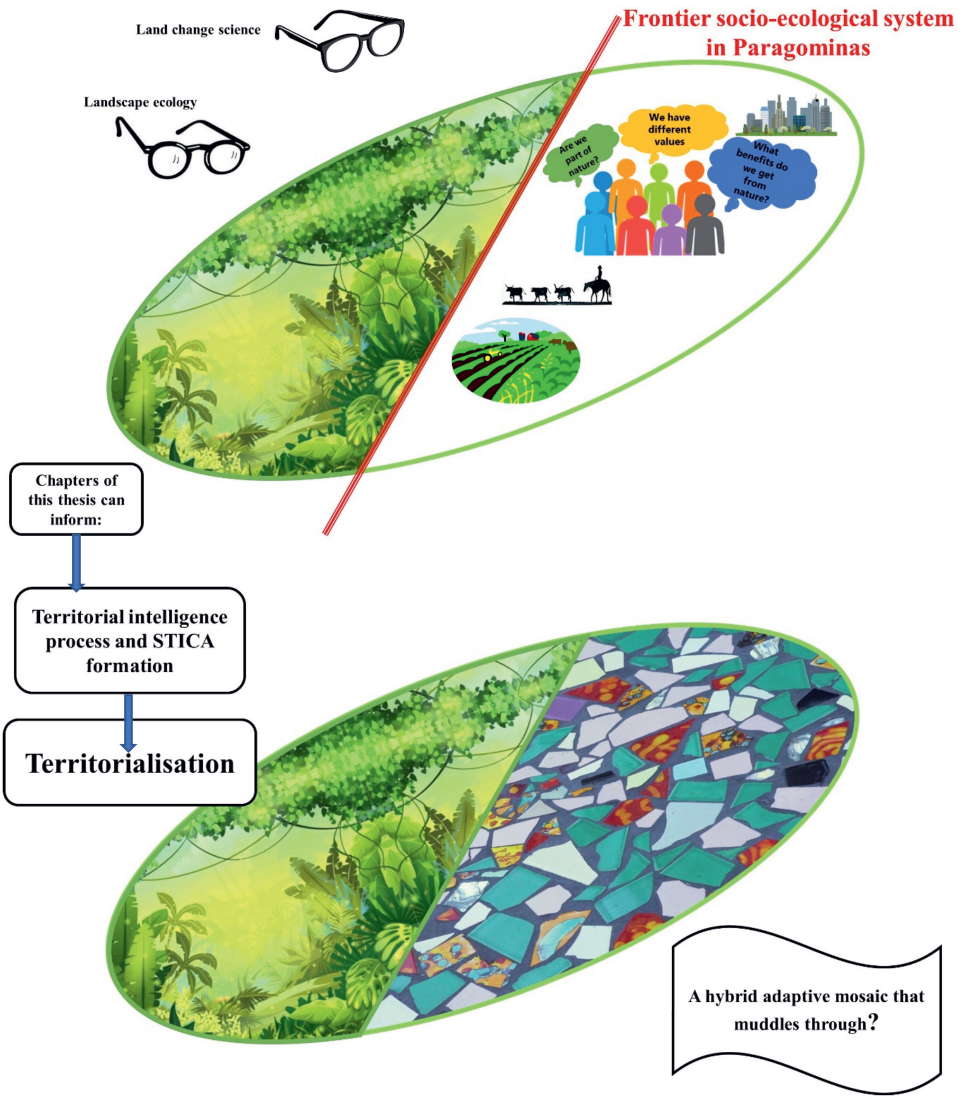

Figure 6.3. Integrative land change science and landscape ecology approach used in this thesis to analyze the frontier socio-ecological system of Paragominas. The outcomes of this thesis can inform the current territorial intelligence process and STICA formation in Paragominas towards the territorialization of the landscape. A trajectory in this process could be gearing towards an adaptive mosaic that through endogenous governance processes consolidates a land system architecture (landscape structure) that combines land sparing and land sharing approaches to enhance ecosystem services multifunctionality.

6.7 Concluding remarks

Altogether, my findings show that given the influence of global markets for agricultural commodities and landscape heterogeneity (i.e., trade-offs between production and forest conservation, agricultural intensification patterns, and perceptions), enhancing landscape multifunctionality in Paragominas will rely to a significant extent on land architecture designs and local governance initiatives that galvanize the recognition of the forest as an integral part of socio-economic development. Fluctuations of economic cycles and commodity prices as well as land speculation over the last five decades, have been dominant drivers for deforestation rates ups and downs in the Brazilian Amazon and the 2004-2012 decline was no exception to this.

Deforestation has been on the rise ever since with a worrisome trend exacerbated by forest fires and a convoluted political and social national context. Changes that structurally decouple deforestation from rural development in the long term, nevertheless, are still missing in the region. Deforestation happens because the short and local term benefits of it are perceived to outweigh its negative impacts in the long run at larger scales. Thus, recognition of the forest as an essential part of socio-economic development to foster forest conservation and transitions in Paragominas, as in anywhere else, requires that stakeholders and decision makers reflect on their own perceptions and values (Garcia et al., 2020).

The integration of the different methodologies I applied throughout the chapters of this thesis (i.e., a spatially explicit ecosystem services supply-demand analytical framework, a farm typology, Q methodology, and anticipatory scenarios for carbon storage), and the concepts I cited in this section intended to describe a socio-ecological system in which causal links are multiple and complex. This application of multiple methodologies and epistemological perspectives (land change science and landscape ecology) constituted the operationalization of a landscape approach that allowed me to develop the "building blocks" of this thesis to capture landscape heterogeneity and analyze it. Even though the focus of this thesis was on causal effects (i.e., Chapter 2: the effects of different combinations of pedo-morphology and land use on ecosystem services; Chapter 3: effects of land constriction and market and policy dynamics on agricultural intensification; Chapter 4: the effects of socio-economic conditions on forest conservation perceptions; Chapter 5: effects of landscape structure and land sparing-land sharing configurations on carbon storage), and focus on causal mechanisms was limited, the findings of my thesis can help framing further research in frontiers of the Amazon or emerging frontiers in other parts of the world (cf. Bey et al., 2020).

Furthermore, the descriptive research I conducted can steer and stimulate learning and trust formation among social actors in Paragominas. As suggested by Garcia et al. (2020), by asking how the system works rather than asking why (reasons and postures), collaboration and trust is more likely to emerge among diverse stakeholders. The closer our understanding of the actual mechanistic processes shaping the biophysical landscape is, the smaller the gap between the intended consequences of actions and their effective impact (Garcia et al., 2020).

The potential of the results of this thesis as boundary objects (i.e., objects that facilitate communication across different group of stakeholders) (Fujimura, 1992; Guston, 2001; Lundgren, 2020) for STICA formation was not tested and constitutes another limitation of this thesis. However, there is an alignment between a process of territorial intelligence and the notion of an adaptive mosaic to generate a basket of options for agricultural diversification and intensification, and its reconciliation with forest conservation. Thus, as a highly iterative process, land use planning and prospects of a territorialization process in Paragominas can use the results or part of the results I developed. The municipal zoning of potential trade-off areas of ecosystem services (Chapter 2) offers the possibility to discuss spatial differences at the municipal scale to derive a spatial guideline for land use allocation for landscape multifunctionality. The farm and landholder typologies I developed, provide information on diversity of farming systems and the perceptions of landholders regarding Legal Reserves that can be used in workshops to stimulate self-reflection and derive proposals for land use planning that facilitates agricultural intensification and forest conservation. Similarly, the anticipatory scenarios (Chapter 5) can be used in workshops as a visual aid to discuss and inspire new visions for the landscape in the mid and long term.

A recurrent situation in agricultural landscapes seems to be that as long as the forest is unable to compete with other land uses in terms of short-term profits, it will be cleared. Mechanisms that compensate for this such as PES and REDD+ seem to ameliorate this effect in some instances but notwithstanding the continued emergence of global initiatives and policy instruments, forest loss continues around the globe particularly in tropical regions (Garcia et al., 2020). Forest and natural capital loss is prompted by a fundamentally distorted conceptualization of the world in which the biophysical system is treated as a sub-system of an integrated economic global system of market competition, commodity flows and intellectual property (Passet, 2011). A much more accurate conception of reality of course, is one of an economic subsystem embedded in a human subsystem that in turn is embedded in a global live macrosystem of matter and energy flows i.e., the biosphere (Passet, 1979).

Agro-industrial intensification lies at the center of this detrimental prioritization of the economic subsystem over the biosphere. Approaches that attempt to adjust this include climate smart agriculture, which combines digital technologies and takes into account spatial allocation of land uses to optimize resources (Debref, 2017). Agroecological approaches promote the development of biodiverse agroecosystem able to sustain its own functioning in variable and diverse farm conditions (Altieri, 2002). Regenerative agriculture proposes soil conservation farming practices as the entry point to regenerate and contribute to the provision of multiple ecosystem services (Schreefel et al., 2020). These approaches to agriculture should be brought into the discussion table by a territorial process in Paragominas to guide a paradigm shift in which the biosphere is prioritized over finances and markets devoted to “economic growth”. The current COVID 19 pandemic has been yet another reminder of the perils associated with the advancement of large scale industrial monocultures at the expense of natural habitats that cause the spilling over of viruses and bacteria into livestock and human communities (Altieri and Nicholls, 2020).

Nevertheless, industrial agriculture and its incongruity with the way the biosphere operates is just a symptom of a global culture that is based on affluent consumption and that feeds an economic system that exploits nature and animals (including humans) by equating prosperity with GDP growth. There is ample evidence that the consumption by affluent households around the globe is one of the unmistakable determinants and accelerators of global environmental and social negative impacts on the Earth’s life-sustaining functions (Wiedmann et al., 2020).

In this global context, the social function of science is to elicit societal dialogue concerning a bioeconomic scientific paradigm in which the constraints and rules of the biosphere are pivotal (Debref, 2017). Multi, inter and transdisciplinary research to engage with society in broad discussions concerning solutions and policies is critical to generate visions, scenarios and pathways for a sustainable, prosper life within the boundaries of the biosphere and with less material affluence (Wiedmann et al., 2020). At the same time, these interactions may be able to steer altruism towards other humans, animals and the natural environment, which is one of the main values that can lead individuals toward pro-environmental attitudes and behaviors (Dietz et al., 2005). In this sense, it is essential to reject the simplistic idea that reduces a prosper society to the sum of individual decisions pursuing individual wellbeing.

In this thesis I showed that engagement with landholders from the industrial agricultural sector is crucial to envision alternative pathways for agricultural intensification and forest conservation in the Brazilian Amazon. Mere condemnation and stigmatization of these social actors is not only useless but otherizes and alienates people of different backgrounds and values, ultimately perpetuating stagnation and engendering unproductive conflict. The scientific endeavor thus, must focus on producing information that brings people together and are able to envision common goals, but more importantly agree on their understanding of the world.

Finally, while the concept of the frontier was useful to understand past and ongoing developments in an Amazonian socio-ecological system, I argue that in looking ahead, the imagery and symbolism of the frontier should be dissolved in the context of agroecosystems. The notion of "a frontier" defining the human-nature interaction obscures the obvious yet evasive recognition that we too, are part of nature. Thus, I propose the notion of "land merging", as opposed to "land sparing" and beyond "land sharing", to keep on theorizing potential concepts and approaches for land use system decisions and agroecosystem management that materialize the dissolution of the frontier. It is like this that a scientific endeavor could enlighten societies not only in our understanding of the world, but in our understanding of ourselves.

6.8 Acknowledgements

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Summary
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Summary

Sustainable food production requires approaches that reconcile agricultural production with the conservation and sustainable use of natural resources, biodiversity, and associated ecosystem services. In tropical agroecosystems the expansion of the agricultural frontier usually signifies the loss of forest cover in detriment of natural capital and ecosystem services. In the Brazilian Amazon region, extensive cattle ranching was introduced in the 1960s mainly for the purpose of securing land ownership at the expense of forest cover. However, between 2004 and 2012, policy measures, public-private coalitions and declining market trends for commodities induced a 70% reduction in deforestation in the Amazon. In the municipality of Paragominas (19,342 km^2) in the eastern Amazon region, this process began in 2008 after the Green Municipality initiative forged a pact among rural elites to end large-scale deforestation and monitor private forests within landholdings (i.e., Legal Reserves). These zero-deforestation measures have stimulated agricultural intensification in the region to increase production in already open areas as clearing of forest was constrained. Nevertheless, since 2014 deforestation rates in the Amazon have been on the rise again, casting doubts on the long-term effectiveness of command-and-control measures to structurally decouple agriculture from deforestation.

Therefore, it is unclear which pathways can sustain and further improve synergies between forest protection and rural development in the eastern Amazon region. Specifically, it is unclear what types of land use spatial arrangements can reconcile forest conservation and agricultural production, and there is no clarity on what farming systems emerge as a result of reduced access to land. There is also limited understanding in regard perceptions of farmers and landholders on policy changes that first convoked colonizers to deforest, and then punished deforestation. Therefore, there is an urgent need to inform on-going land use planning and governance initiatives in the region to enable rural development and forest conservation within the context of increasing economic and environmental pressures. Guided by the above knowledge gaps, I adopted a landscape approach to conceptualize a frontier socio-ecological system in the Paragominas municipality. I addressed these research questions by applying a variety of methodologies to assess biophysical characteristics of the landscape, land use and land cover patterns, agricultural intensification strategies, landholder's perceptions, and landscape scenarios.

In Chapter 2, I applied the Functional Land Management framework to assess the supply and demand of three ecosystem services in a spatially explicit manner to identify areas of (mis)matches and trade-offs between 1) carbon storage, 2) agricultural commodity production,

and 3) habitat for biodiversity in the municipality of Paragominas. The supply of these ecosystem services was informed by a literature review for the various combinations of pedo-morphological characteristics and land uses in the region. The demand for these ecosystem services was mapped based on federal and state policy targets. Mapping the supply and demand of carbon storage indicated that half of the carbon in the region is stored in remnants of undisturbed forest which cover only a third of the municipality. Demand for habitat for biodiversity in terms of forested area is met, but it does not guarantee safeguarding biodiversity. Roughly a third of the territory has a relatively poor quality of habitat for biodiversity even if compliant with legislation. Concerning commodity production, I identified areas where both the supply and the demand to increase production are relatively high due to road access and low intensification costs. The demand for agricultural production can eventually incentivize the expansion of agriculture on fertile soils, which could compromise forest conservation targets. These findings suggest that the simultaneous delivery of multiple ecosystem services may require land use pathways that combine land sparing and land sharing approaches.

In Chapter 3, I conducted an analysis at the farm level to assess how processes of agricultural intensification unfold in a context of land constriction elicited by zero-deforestation policies. I surveyed 40 medium and large farms (average size ranging between 800-1000 ha) in Paragominas and developed a farm typology based on farm structural variables, including farm area size, land use composition, land ownership, farm age, yields, and production orientation. I identified three farm types: 1) *Extensive cattle-soybean ranches,* which used to be traditional cattle ranches that are gradually converting pasture areas to soybean monocultures in open areas with clayey soils, 2) *Integrated farms* are integrated agro-pastoral and silvo-pastoral systems run by the wealthiest agribusiness firms in the region, and 3) *Soybean-based farms* specialize on soybean production with varying area size and location across the municipality. This farm typology suggested a range of agricultural intensification from extensive cattle farms to soybean-based and integrated farms. The process of agricultural intensification in Paragominas has been steered by an agro-industrial production model under a low-deforestation context, but it is not clear whether deforestation will remain under control in the mid and long term. This farm typology can be a tool to identify diversification pathways tailored to the different farm types I described in this chapter to incorporate more diversified production systems, such as agroforestry and other tree-based integrated systems.

In Chapter 4, I assessed how medium and large-scale landholders perceive the requirement of Legal Reserves. This is a critical law in Brazil to protect forest on private lands, as they cover roughly a third of the national territory. While Legal Reserves have major implications for forest conservation in the Amazon, their implementation requires a better understanding of medium and large landholders' perceptions towards this forest conservation policy tool. I applied Q methodology, a technique developed in the field of psychology to identify perceptions of landholders on Legal Reserves and its link to agricultural intensification in Paragominas. I conducted 31 interviews in which landholders sorted 36 statements in a quasi-normal distribution array. I identified three groups of landholders: 1) *Agribusiness-conservation coexistence enthusiasts* (n=18) were interested to explore alternative landscape designs and legislation that may facilitate forest conservation and agricultural intensification; 2) *Policy complacent-market responders* (n=7) showed no interest in Legal Reserves reforms and were the most market-driven group; 3) *Conservation-development antagonists* (n=4) held the most critical views against Legal Reserves and perceived these as an obstacle for their production goals. While Paragominas has kept deforestation rates under control since 2010, addressing persisting forest degradation and fragmentation remains a key priority. Therefore, there is a need to develop novel governance initiatives that account for multi-stakeholder perceptions on forest conservation and agricultural intensification. The results of this chapter provide insights on landholders' perceptions on Legal Reserves that can inform a dialogue at the municipal level aiming at reconciling forest conservation and sustainable agricultural intensification.

In Chapter 5, I assessed the relationship between landscape structure and the capacity of the landscape to store carbon based on anticipatory scenarios at the municipality level. Land sparing and land sharing are widespread concepts describing two contrasting spatial land use allocation strategies to reconcile habitat for biodiversity conservation and agricultural production. Nevertheless, this debate has put insufficient attention on other provisioning and regulating ecosystem services, such as carbon storage. Furthermore, assessments of hybrid approaches beyond the apparent dichotomy are limited. In this chapter, I explored potential effects of different landscape structures (i.e., land sparing and land sharing) on carbon storage in the soil and in aboveground biomass. I collected secondary data from the literature and applied the spatially explicit Carbon Storage and Sequestration InVEST model to estimate carbon storage under eight anticipatory landscape scenarios. Three scenarios represented an increase of carbon storage in relation to the 2015 baseline, i.e., the *Natural regeneration scenario* (+14.3%), the *Caco-oil palm-based agroforestry scenari*o (+2.4%), and the *Hybrid mosaic landscape scenario* (+10.6%). Scenarios where agricultural expansion resulted in deforestation indicated substantial carbon losses (-12.7 and -40.6%), while scenarios based on agroforestry systems

resulted in slight carbon losses (-1.3 to -4.6%). The results of this chapter highlighted the importance of natural regeneration of secondary forests as a management strategy to enhance carbon storage in the landscape. Furthermore, these findings suggested that combining land sparing and land sharing strategies at the municipal scale can be a useful model to inform policy-making decisions towards landscape multifunctionality in Paragominas.

Altogether, my findings show that given the influence of global markets, diversity of landholders' perceptions, intensification patterns, and trade-offs between ecosystem services, enhancing landscape multifunctionality in Paragominas will depend to a large extent on landscape designs and governance processes that are able to revalorize forests as an integral part of socio-economic development. Such revalorization could guide farmers and landholders' decisions towards agricultural intensification strategies beyond the prevailing agro-industrial model, sustained by an ingrained land sparing paradigm in the region. The results of my thesis can inform current policy and governance developments in Paragominas where the spatial allocation of areas suitable for agricultural intensification and forest conservation is increasingly taking a central role in the discussion to develop pathways for landscape multifunctionality.

Perspectivas de paisagens multifuncionais na Amazônia: análise das estratégias dos agricultores, percepções e cenários em uma fronteira agrícola

Sumário

A produção sustentável de alimentos requer abordagens que conciliem a produção agrícola com a conservação e o uso sustentável dos recursos naturais, biodiversidade e serviços ecossistêmicos associados. Nos agroecossistemas tropicais, a expansão da fronteira agrícola geralmente significa a perda da cobertura florestal e consequentemente do capital natural e dos serviços ecossistêmicos. Na região amazônica brasileira, a pecuária extensiva foi introduzida nos anos 60, principalmente com o objetivo de garantir a posse da terra em detrimento da cobertura florestal. Entretanto, entre 2004 e 2012, medidas políticas, coalizões público-privadas e tendências declinantes do mercado de commodities propiciaram uma redução de 70% no desmatamento na Amazônia. No município de Paragominas (19.342 km²), na região leste da Amazônia, este processo começou em 2008 depois que a Iniciativa do Município Verde estabeleceu um pacto entre a sociedade local para acabar com o desmatamento em larga escala e monitorar as florestas privadas dentro de propriedades rurais (Reservas Legais). Essas medidas de desmatamento zero estimularam a intensificação da agricultura na região para aumentar a produção em áreas já abertas, uma vez que o desmatamento de florestas foi limitado. Entretanto, desde 2014, as taxas de desmatamento na Amazônia têm aumentado novamente, lançando dúvidas sobre a eficácia a longo prazo das medidas de comando e controle para dissociar estruturalmente a agricultura do desmatamento.

Portanto, não está claro quais caminhos podem sustentar e melhorar ainda mais as sinergias entre a proteção das florestas e o desenvolvimento rural na região leste da Amazônia. Especificamente, está incompreensível tipos de arranjos espaciais de uso da terra que podem conciliar a conservação e a restauração florestal com a produção agrícola, e não há clareza sobre quais sistemas agrícolas surgem como resultado da redução do acesso a novas terras. Há também um entendimento limitado sobre as percepções dos agricultores e proprietários de terra sobre mudanças políticas que primeiro convocaram colonizadores para desmatar, e depois puniram o desmatamento. Portanto, há uma necessidade urgente de informar o planejamento de uso da terra e as iniciativas de governança que são capazes de estabelecer o desenvolvimento rural e a conservação florestal e ambiental dentro do contexto das contínuas pressões econômicas e ambientais na região. Guiado pelas lacunas de conhecimento acima, foi adotada

uma abordagem paisagística para conceituar o sistema socioambiental de fronteira de Paragominas. Foram abordadas questões de pesquisa através da aplicação de uma variedade de metodologias para avaliar características biofísicas, incluindo padrões de uso e cobertura da terra, estratégias de intensificação agrícola, percepções dos proprietários de terra e cenários de uso da terra.

No Capítulo 2, foi aplicado o conceito de Gestão Funcional da Terra (Functional Land Management) para avaliar a oferta e demanda de três serviços ecossistêmicos de forma espacialmente explícita para identificar áreas incompatíveis e áreas de compromissos (*trade-offs*) entre 1) armazenamento de carbono, 2) produção de commodities agrícolas, e 3) habitat para a biodiversidade no município de Paragominas. A oferta destes serviços ecossistêmicos foi obtida por uma revisão bibliográfica para várias combinações de características pedomorfológicas e usos da terra na região. A demanda por estes serviços ecossistêmicos foi mapeada com base em metas de políticas federais e estaduais. O mapeamento da oferta e demanda de armazenamento de carbono indicou que metade do carbono na região é armazenada em remanescentes de floresta não perturbada que cobrem apenas um terço do município. A demanda por habitat para biodiversidade em termos de área florestal é atendida, mas isso não garante a proteção da biodiversidade. Aproximadamente um terço do território tem uma qualidade relativamente pobre de habitat para a biodiversidade, mesmo que esteja de acordo com a legislação. Quanto à produção de commodities, foram identificadas áreas onde tanto a oferta quanto a demanda para aumentar a produção são relativamente altas devido ao acesso rodoviário e aos baixos custos de intensificação. A demanda pela produção agrícola pode eventualmente incentivar a expansão da agricultura em solos férteis, o que poderia comprometer as metas de conservação das florestas. Estas descobertas sugerem que a prestação simultânea de múltiplos serviços ecossistêmicos pode exigir organizações de uso da terra que combinem a especialização e o compartilhamento (land sharing é land sparing).

No Capítulo 3, foi realizada uma análise em nível de fazenda para avaliar como os processos de intensificação agrícola se desdobram em um contexto de acesso limitado à terra, provocado por políticas de desmatamento zero. Foi feita uma pesquisa em 40 fazendas médias e grandes portes (tamanho médio 1000 ha) em Paragominas e foi desenvolvida uma tipologia de fazenda baseada em variáveis estruturais da fazenda, incluindo tamanho da área, composição do uso da terra, propriedade da terra, idade, produtividade e orientação da produção. Foram identificados três tipos de fazendas: 1) *fazendas extensivas de pecuária e soja,* que costumavam ser fazendas tradicionais de gado que estão gradualmente convertendo áreas de pastagem em monoculturas de soja em áreas abertas com solos argilosos, 2) *fazendas integradas* são sistemas de integração lavoura-pecuária e pecuária - floresta, e 3) *fazendas cultivadas com soja* especializadas na produção de soja com área e localização variáveis em todo o município. Estas tipologias de fazendas sugeriram um gradiente crescente de intensificação agrícola de fazendas extensivas de pecuária, para fazendas baseadas na soja e fazendas integradas. O processo de intensificação agrícola em Paragominas tem sido conduzido por um modelo de produção agroindustrial sob um contexto de baixo desmatamento, mas não está claro se o desmatamento permanecerá sob controle a médio e longo prazo. Esta tipologia agrícola pode ser uma ferramenta para identificar caminhos de diversificação adaptados aos diferentes tipos de fazendas descritos neste capítulo para incorporar sistemas produtivos mais diversificados, tais como a agrofloresta e outros sistemas integrados que tornam mais eficiente a cobertura arbórea na paisagem.

No Capítulo 4, foi avaliada como os proprietários de terras de médio e grande porte percebem a exigência de Reservas Legais. Esta é uma lei importante e fundamental no Brasil para proteção de florestas em terras privadas, que abrangem cerca de um terço do território nacional. Embora as Reservas Legais tenham grandes implicações para a conservação florestal na Amazônia, sua implementação requer um melhor entendimento das percepções dos proprietários de terras de médio e grande porte em relação a esta ferramenta de política florestal em Paragominas. Foi aplicada a metodologia Q, uma técnica desenvolvida no campo da psicologia, para identificar as percepções dos proprietários de terras sobre as Reservas Legais e sua ligação com a intensificação da agricultura. Foram realizadas 31 entrevistas nas quais os proprietários de terra classificaram 36 declarações em uma matriz de distribuição quase normal. Foram identificados três grupos de proprietários de terras: 1) *Os entusiastas da coexistência agronegócio-conservação* (n=18) estavam interessados em explorar projetos paisagísticos e legislações alternativas que pudessem facilitar a conservação das florestas e a intensificação da agricultura; 2) *Os conectados ao mercado* (n=7) não mostraram interesse nas reformas das Reservas Legais e eram o grupo mais orientado para o mercado; 3) *Os antagonistas da conservação-desenvolvimento* (n=4) tinham os pontos de vista mais críticos contra as Reservas Legais e os encaravam como um obstáculo para suas metas de produção. Embora em Paragominas as taxas de desmatamento tenham se mantido sob controle desde 2010, lidar com a persistente degradação e fragmentação das florestas continua sendo uma prioridade chave. Portanto, existe a necessidade de desenvolver novas iniciativas de governança que levem em conta as percepções de múltiplos atores sobre conservação florestal e objetivos de intensificação agrícola. Os resultados deste capítulo fornecem conhecimento sobre as percepções dos proprietários de terras sobre Reservas Legais que podem informar um diálogo em nível municipal visando conciliar a conservação florestal e a intensificação agrícola sustentável em Paragominas.

No Capítulo 5, foi avaliada a relação entre a estrutura da paisagem e a capacidade da paisagem de armazenar carbono, com base em cenários antecipatórios ao nível municipal. *Land sparing* (divisão entre áreas de preservação e áreas de uso humano, modo de reserva) e *land sharing* (compartilhamento de terra entre preservação e outros usos da terra, modo de compartilhamento) são conceitos comuns que descrevem duas estratégias de alocação espacial de uso da terra contrastantes para conciliar habitat para conservação da biodiversidade e produção agrícola. No entanto, este debate tem dado atenção insuficiente a outros serviços ecossistêmicos de abastecimento e regulação, tais como o armazenamento de carbono. Além disso, as avaliações de abordagens híbridas além da aparente dicotomia são limitadas. Neste capítulo, foram explorados os efeitos potenciais de diferentes configurações de paisagem sobre o armazenamento de carbono no solo e na biomassa acima do solo. Dados secundários da literatura foram coletados e aplicados no modelo InVEST de armazenamento e sequestro de carbono que distribui espacialmente e estima o armazenamento de carbono sob oito cenários de paisagem antecipatórios. Três cenários representaram um aumento do armazenamento de carbono em relação à linha de base de 2015, ou seja, o *cenário de regeneração natural* com um aumento de +14,3%, o cenário *agroflorestal baseado na palmeira e cacau* com +2,4%, e o *cenário do mosaico híbrido* com um aumento de +10,6%. Cenários onde a expansão agrícola resultou em desmatamento indicaram perdas substanciais de carbono (-12,7 e -40,6%), enquanto cenários baseados em sistemas agroflorestais resultaram em pequenas perdas de carbono (-1,3 a -4,6%). Os resultados deste capítulo destacaram a importância da regeneração natural das florestas secundárias como uma estratégia de manejo para melhorar o armazenamento de carbono. Além disso, estes resultados sugeriram que a combinação de estratégias de terra de modo reserva e modo compartilhamento em escala municipal pode ser um modelo útil para informar a tomada de decisões políticas para a multifuncionalidade da paisagem em Paragominas.

No conjunto, meus resultados mostram que, dada a influência dos mercados globais, a diversidade de percepções dos proprietários de terras, os padrões de intensificação e os trade-offs entre os serviços ecossistêmicos, a melhoria da multifuncionalidade da paisagem em Paragominas dependerá em grande parte dos projetos de organização da paisagem e da governança local que são capazes de revalorizar as florestas como parte integrante do desenvolvimento socioeconômico. Tal revalorização poderia orientar as decisões dos agricultores e proprietários de terras para estratégias de intensificação agrícola sustentável além do modelo agroindustrial atual, sustentado por um paradigma de modo reserva (land sparing) arraigada na região. Os resultados de minha tese podem informar os desenvolvimentos políticos em andamento em Paragominas, elucidando um processo de governança inovador endógeno onde a alocação espacial de áreas adequadas para a intensificação agrícola e conservação florestal está assumindo um papel central na discussão para desenvolver paisagens multifuncionais.

Perspectives pour des paysages multifonctionnels en Amazonie: analyse des stratégies, des perceptions et des scénarios des agriculteurs sur une frontière agricole

Résumé

La production alimentaire durable exige des approches qui concilient la production agricole avec la conservation et l'utilisation durable des ressources naturelles, de la biodiversité et des services écosystémiques associés. Dans les agroécosystèmes tropicaux, l'extension de la frontière agricole signifie généralement la perte de la couverture forestière, et donc du capital naturel et des services écosystémiques. En Amazonie brésilienne, l'élevage extensif de bétail a été développé au cours des années 1960, avec une fonction d'appropriation foncière, au détriment du couvert forestier. Cependant, entre 2004 et 2012, des mesures politiques, des coalitions public-privé et des tendances à la baisse sur le marché des matières premières ont permis de réduire de 70 % la déforestation en Amazonie. Dans la municipalité de Paragominas (19, 342 km²), en Amazonie orientale, ce processus a débuté en 2008 après que l'initiative pour une « Municipalité Verte » ait établi un pacte au sein de la société locale pour mettre fin à la déforestation à grande échelle et surveiller les forêts privées (réserves légales). Ces mesures visant la déforestation zéro ont stimulé l'intensification de l'agriculture dans la région, afin d'augmenter la production dans les zones déjà ouvertes. Cependant, depuis 2014, les taux de déforestation en Amazonie ont à nouveau augmenté, remettant en question l'efficacité à long terme des mesures de « commandement et de contrôle » pour découpler définitivement l'agriculture de la déforestation.

Les voies de développements pouvant soutenir et améliorer encore d'avantage les synergies entre la protection des forêts et le développement rural en Amazonie orientale restent donc incertaines. Plus précisément, il est difficile de déterminer quels types d'aménagement du territoire peuvent concilier la conservation et la restauration des forêts avec la production agricole, sans savoir quels systèmes agricoles résulteront de la réduction de l'accès à de nouvelles terres. On comprend également mal la perception qu'ont les agriculteurs et les propriétaires terriens à propos des changements politiques qui ont d'abord appelé les colons à déboiser, avant de sanctionner la déforestation. Il est donc urgent de mettre en place des initiatives d'aménagement du territoire et de gouvernance, capables d'établir le développement

rural et la conservation des forêts et de l'environnement dans le contexte des pressions économiques et environnementales actuelles. Guidée par les lacunes de connaissances ci-dessus, une approche paysagère a été adoptée pour conceptualiser le système socio-environnemental du front pionnier de Paragominas. Les questions de recherche ont été abordées en appliquant diverses méthodologies pour évaluer les caractéristiques biophysiques, notamment l'utilisation des terres et les modèles de couverture des sols, les stratégies d'intensification agricole, les perceptions des propriétaires fonciers et les scénarios d'utilisation des terres.

Au chapitre 2, le concept de Gestion Fonctionnelle des Terres (Functional Land Management) a été appliqué pour évaluer l'offre et la demande de trois services écosystémiques de manière spatialement explicite afin d'identifier les zones incompatibles et les compromis entre 1) le stockage du carbone, 2) la production de produits agricoles et 3) l'habitat pour la biodiversité dans la municipalité de Paragominas. L'offre de ces services écosystémiques a été obtenue par une revue bibliographique avec diverses combinaisons de caractéristiques pédo-morphologiques et d'utilisations des terres dans la région. La demande de ces services écosystémiques a été cartographiée sur la base des objectifs politiques du gouvernement fédéral et des États. La cartographie de l'offre et de la demande de stockage du carbone a indiqué que la moitié du carbone dans la région est stockée dans des vestiges forestiers non perturbés qui ne couvrent qu'un tiers de la municipalité. La demande d'habitat pour la biodiversité en termes de surface forestière est satisfaite, mais cela ne garantit pas la protection de la biodiversité. Environ un tiers du territoire présente une qualité d'habitat relativement médiocre pour la biodiversité, bien que conforme à la législation. Concernant la production de matières premières, des zones ont été identifiées où l'offre et la demande en augmentation de la production sont relativement élevées en raison de l'accès routier et des faibles coûts d'intensification. La demande de production agricole peut éventuellement encourager l'expansion de l'agriculture sur des sols fertiles, compromettant alors les objectifs de conservation des forêts. Ces résultats suggèrent que la fourniture simultanée de multiples services écosystémiques peut nécessiter que les organisations d'utilisation des terres combinent spécialisation et partage (land sparing est land sharing).

Au chapitre 3, une analyse au niveau de l'exploitation a été réalisée pour évaluer comment les processus d'intensification agricole se déroulent, dans un contexte d'accès limité aux terres causé par les politiques de déforestation zéro. Une enquête a été menée sur 40 exploitations moyennes et grandes (taille moyenne de 1000 ha) à Paragominas, suivie d’une typologie des exploitations élaborée sur la base de variables structurelles de l'exploitation, notamment la taille de la zone, la composition de l'utilisation des terres, la propriété foncière, l'âge, la productivité et l'orientation de la production. Trois types d'exploitations ont été identifiés: 1) les *exploitations bovines et de soja extensives,* qui étaient autrefois des élevages bovins traditionnels convertissant progressivement les zones de pâturage en monocultures de soja dans les zones ouvertes aux sols argileux, 2) *les exploitations intégrées,* qui sont des systèmes d'intégration culture-élevage et bétail - forêt, et 3) les *exploitations de soja* spécialisées dans la production de soja, dont la superficie et l'emplacement varient dans toute la municipalité. Ces types d'exploitations ont laissé entrevoir un gradient croissant d'intensification agricole, allant des élevages bovins extensifs aux fermes intégrées et à base de soja. Le processus d'intensification agricole à Paragominas a été conduit par un modèle de production agro-industriel dans un contexte de faible déforestation, mais il n'est pas certain que la déforestation reste sous contrôle à moyen et long terme. Cette typologie agricole peut être un outil pour identifier des voies de diversification adaptées aux différents types d'exploitations décrits dans ce chapitre afin d'intégrer des systèmes de production plus diversifiés, tels que l'agroforesterie et d'autres systèmes intégrés qui rendent plus efficace le couvert végétal dans le paysage.

Au chapitre 4, il a été évalué comment les propriétaires fonciers de moyenne et grande taille perçoivent l'exigence de réserves légales. Il s'agit d'une loi importante et fondamentale au Brésil sur la protection des forêts sur les terres privées, qui couvrent environ un tiers du territoire national. Bien que les réserves légales aient de grandes implications pour la conservation des forêts en Amazonie, leur mise en œuvre nécessite une meilleure compréhension des perceptions des moyens et grands propriétaires terriens concernant cet outil de politique forestière à Paragominas. La méthodologie Q, une technique développée dans le domaine de la psychologie, a été appliquée pour identifier les perceptions des propriétaires fonciers sur les réserves légales et leur lien avec l'intensification de l'agriculture. 31 entretiens ont été menés, au cours desquels les propriétaires fonciers ont classé 36 déclarations dans une matrice de distribution presque normale. Trois groupes de propriétaires fonciers ont été identifiés: 1) les *partisans de la conservation par l'agrobusiness* (n=18) étaient intéressés par l'exploration de projets paysagers alternatifs et de législations qui pourraient faciliter la conservation des forêts et l'intensification de l'agriculture; 2) *ceux qui étaient liés au marché (*n=7) ne montraient aucun intérêt pour les réformes des réserves légales et étaient le groupe le plus orienté vers le marché; 3) les *antagonistes de la conservation-développement* (n=4) avaient les opinions les plus critiques à l'égard des réserves légales et les considéraient comme un obstacle à leurs objectifs de production. Bien qu'à Paragominas, les taux de déforestation soient restés sous contrôle depuis 2010, la lutte contre la dégradation et la fragmentation persistante des forêts reste une priorité essentielle. Il est donc nécessaire d'élaborer de nouvelles initiatives de gouvernance qui tiennent compte des perceptions des multiples acteurs sur les objectifs de conservation des forêts et d'intensification agricole. Les résultats de ce chapitre fournissent des connaissances sur les perceptions des propriétaires fonciers concernant les réserves légales qui peuvent alimenter un dialogue au niveau municipal visant à concilier la conservation des forêts et l'intensification agricole durable à Paragominas.

Au chapitre 5, la relation entre la structure du paysage et la capacité du paysage à stocker le carbone a été évaluée, sur la base de scénarios d'anticipation au niveau municipal. *Land sparing* (division entre les zones de conservation et les zones d'utilisation humaine, mode de spécialisation) et *Land sharing* (partage des terres entre la conservation et les autres utilisations des terres, mode de partage) sont des concepts communs qui décrivent deux stratégies contrastées d'allocation spatiale des terres pour concilier l'habitat pour la conservation de la biodiversité et la production agricole. Toutefois, ce débat n'a pas accordé suffisamment d'attention aux autres services écosystémiques d'approvisionnement et de régulation, tels que le stockage du carbone. En outre, les évaluations des approches hybrides au-delà de la dichotomie apparente sont limitées. Dans ce chapitre, les effets potentiels de différentes configurations de paysages sur le stockage du carbone dans le sol et la biomasse aérienne ont été explorés. Des données secondaires issues de la littérature ont été collectées et appliquées au modèle de stockage et de séquestration du carbone InVEST qui distribue et estime le stockage du carbone dans huit scénarios de paysage d'anticipation. Trois scénarios représentaient une augmentation du stockage du carbone par rapport au niveau de référence de 2015, à savoir le scénario de *régénération naturelle* avec une augmentation de +14,3 %, le scénario d'*agroforesterie basé sur le palmier et le cacao avec* +2,4 %, et le scénario de *mosaïque hybride* avec une augmentation de +10,6 %. Les scénarios dans lesquels l'expansion agricole a entraîné la déforestation ont indiqué des pertes substantielles de carbone (-12,7 et -40,6 %), tandis que les scénarios basés sur des systèmes agroforestiers ont entraîné de faibles pertes de carbone (-1,3 à -4,6 %). Les résultats de ce chapitre ont souligné l'importance de la régénération naturelle des forêts secondaires comme stratégie de gestion pour améliorer le stockage du carbone. En outre, ces résultats suggèrent que la combinaison de stratégies foncières en mode réserve et de partage à l'échelle municipale peut être un modèle utile pour aiguiller l'élaboration des politiques en faveur de la multifonctionnalité du paysage à Paragominas.

Dans l'ensemble, les résultats montrent que, compte tenu de l'influence des marchés mondiaux, de la diversité des perceptions des propriétaires fonciers, des modèles d'intensification et des compromis entre les services écosystémiques, l'amélioration de la multifonctionnalité du paysage à Paragominas dépendra largement des projets d'organisation du paysage et de la gouvernance locale qui sont capables de revaloriser les forêts en tant que partie intégrante du développement socio-économique. Cette réévaluation pourrait orienter les décisions des agriculteurs et des propriétaires fonciers vers des stratégies d'intensification agricole durable allant au-delà du modèle agro-industriel actuel, soutenu par un paradigme d'économie des terres ancré dans la région. Les résultats de cette thèse pourraient supporter les développements politiques en cours à Paragominas, en élucidant un processus de gouvernance endogène innovatrice où l'allocation spatiale de zones appropriées pour l'intensification agricole et la conservation des forêts assume un rôle central dans la discussion portant sur les voies de développement de paysages multifonctionnels.

Perspectivas para paisajes multifuncionales en el Amazonas: análisis de estrategias, percepciones y escenarios en una frontera agrícola

Resumen

La producción sostenible de alimentos requiere enfoques que reconcilien la producción agrícola con la conservación y el uso sostenible de los recursos naturales, la biodiversidad y los servicios ecosistémicos asociados. En los agroecosistemas tropicales la expansión de la frontera agrícola generalmente representa la pérdida de cobertura forestal y, por lo tanto, del capital natural y servicios ecosistémicos. En la región Amazónica Brasileña, la ganadería extensiva se introdujo, principalmente, en la década de 1960 con el objetivo de asegurar la tenencia de tierra a expensas de la cobertura forestal. Sin embargo, entre los años 2004 y 2012, políticas de conservación, coaliciones público-privadas y una demanda global de productos agrícolas decreciente, dieron lugar a una reducción del 70% de la deforestación en el Amazonas. En el municipio de Paragominas (19,342 km^2), en la región oriental del Amazonas, este proceso comenzó en 2008 después de que la iniciativa "Municipio Verde" estableciera un pacto entre la sociedad local para poner fin a la deforestación de gran escala y monitorear la cobertura forestal dentro de propiedades privadas (Reservas legales). Estas políticas de "deforestación cero" estimularon la intensificación de la agricultura en la región para aumentar la producción en zonas ya deforestadas. Sin embargo, desde el año 2014, las tasas de deforestación en el Amazonas han vuelto a aumentar, lo que pone en duda la eficacia en el largo plazo de medidas de mando y control para evitar la pérdida de cobertura forestal a expensas del crecimiento de la producción agrícola.

En dicho contexto, no existe claridad sobre qué acciones puedan sostener y mejorar la confluencia entre la protección de los bosques y el desarrollo rural en la región Amazónica Oriental. Concretamente, es desconocido el ordenamiento territorial que pueda conciliar la conservación y restauración forestal con la producción agrícola, ni tampoco qué sistemas agrícolas surgen como resultado de la reducción del acceso a nuevas tierras. También hay una comprensión limitada sobre las percepciones de los productores rurales con relación a los cambios legislativos que, en primera instancia, permitieron la deforestación con fines de colonización y, posteriormente, la restringieron y castigaron. Por consiguiente, existe una necesidad urgente de proporcionar información a las actuales iniciativas de planificación de uso

de tierra y gobernanza en la región para que sean capaces de establecer pautas de desarrollo rural y conservación forestal en un contexto de presiones económicas y ambientales. Guiados por las lagunas de conocimiento mencionadas, se ha adoptado un enfoque paisajístico para conceptualizar el sistema socio-ecológico de frontera en Paragominas. Dichos puntos de investigación se abordaron aplicando diversas metodologías para evaluar características biofísicas, uso y cobertura de la tierra, estrategias de intensificación agrícola y percepciones locales.

En el capítulo 2, el concepto de Gestión Funcional de la Tierra (Functional Land Management) se aplicó para evaluar la oferta y la demanda de tres servicios ecosistémicos para identificar áreas *de "trade-offs"* entre 1) almacenamiento de carbono, 2) producción agrícola y 3) hábitat para biodiversidad en el municipio de Paragominas. La oferta de estos servicios ecosistémicos se obtuvo mediante una revisión bibliográfica basada en criterios correspondientes a la combinación de diferentes características pedomorfológicas y usos de la tierra en la región. Por otro lado, la demanda de dichos servicios ecosistémicos se mapeó con base a objetivos de políticas federales y estatales. Comparar los mapas de oferta y demanda de almacenamiento de carbono indicó que la mitad del carbono de la región se almacena en remanentes forestales sin perturbación que cubren un tercio del municipio. La demanda por área para hábitat para diversidad biológica en términos de superficie forestal es satisfecha, pero la misma no garantiza la protección de la diversidad biológica. Aproximadamente un tercio del territorio tiene un hábitat de calidad relativamente pobre para la biodiversidad, aunque cumpla con la legislación. En cuanto a la producción agrícola, se han identificado zonas en las que, tanto la oferta como la demanda, para aumentar la producción son relativamente altas debido a que existe acceso por carretera y a los bajos costos de intensificación. La demanda de producción agrícola puede llegar a alentar la expansión de la agricultura en suelos fértiles, lo que podría comprometer objetivos de conservación forestal. Estas conclusiones sugieren que la prestación simultánea de múltiples servicios ecosistémicos requiera que la distribución de utilización de tierra combine estrategias "*land sparing*" y "*land sharing"*.

En el capítulo 3 se realizó un análisis a nivel de finca para evaluar cómo se desarrollan los procesos de intensificación agrícola en un contexto de acceso limitado a la tierra causado por las políticas de deforestación cero. Se realizó una encuesta en 40 medianas y grandes propiedades (tamaño medio de 1,000 ha) en Paragominas y se elaboró una tipología de éstas basada en variables estructurales como el tamaño de finca, composición de uso de la tierra, régimen de propiedad de tierra, edad de la finca, productividad y la orientación de la producción. Se identificaron tres tipos de propiedades: 1) *Fincas ganaderas extensivas y de soja,* las cuales solían ser explotaciones ganaderas tradicionales que gradualmente convirtieron áreas de pasto en monocultivos de soja en áreas abiertas con suelos arcillosos, 2) *Fincas integradas* son sistemas de integración agropecuarias y silvo-pastoriles y 3) *Fincas de soja* especializadas en la producción de soja con extensión y ubicación variables en todo el municipio. Esta tipología de propiedades sugiere la existencia de gradientes de intensificación agrícola, partiendo de las fincas de ganaderías extensivas hasta las fincas de soja e integradas. Dicho proceso de intensificación agrícola en Paragominas ha sido impulsado por un modelo de producción agroindustrial en un contexto de baja deforestación. Sin embargo, no está claro si la deforestación se mantendrá bajo control en el mediano y largo plazos. La tipología agrícola descrita en este capítulo, puede ser una herramienta para identificar vías de diversificación adaptadas a los diferentes tipos de propiedades e incorporar sistemas de producción más diversificados, como agroforestería y sistemas integrados.

En el capítulo 4 se evaluó la percepción de medianos y grandes productores con relación al requisito de Reserva Legal. Esta ley exige la conservación forestal en tierras privadas. Sin embargo, aunque las Reservas Legales tienen grandes implicaciones para la conservación forestal en el Amazonas, ya que cubren un tercio del territorio brasileño, su implementación requiere una mejor comprensión de las percepciones de medianos y grandes propietarios. Se aplicó la metodología Q, una técnica desarrollada en el campo de la psicología, para identificar las percepciones de propietarios de tierras sobre las Reservas Legales y su conexión con la intensificación de la agricultura. Se realizaron 31 entrevistas en las cuales propietarios rurales clasificaron 36 afirmaciones en una matriz de distribución cuasi normal. Se identificaron tres grupos de propietarios de tierras: 1) *Los entusiastas de la coexistencia agroindustria-conservación* (n=18), interesados en explorar proyectos paisajísticos alternativos y de legislación que pudiera facilitar la conservación de los bosques y la intensificación de la agricultura simultáneamente; 2) *Los vinculados al mercado* (n=7) no mostraron interés en reformas para las Reservas Legales pero fueron el grupo más orientado a dinámicas de mercado; 3) *Los antagonistas conservación-desarrollo* (n=4), tuvieron las opiniones más críticas sobre las Reservas Legales y las consideraron un obstáculo para sus objetivos de producción. Aunque en Paragominas las tasas de deforestación han permanecido bajo control desde 2010, abordar la persistente degradación y fragmentación de los bosques sigue siendo una prioridad. Por lo tanto, es necesario elaborar nuevas iniciativas de gobernanza que tengan en cuenta las percepciones de los múltiples actores sobre los objetivos de conservación forestal y la intensificación agrícola. Los resultados de este capítulo proporcionan conocimiento sobre las percepciones de grandes y medianos propietarios que puede servir de base para un diálogo multisectorial a nivel municipal.

En el capítulo 5 se evaluó la relación entre la estructura del paisaje y la capacidad de este para almacenar carbono, con base a escenarios anticipatorios a nivel municipal. *"Land sparing"* (separación entre zonas de conservación y zonas de uso humano) y "*land sharing"* (integración de conservación y otros usos de tierra) son conceptos que describen dos estrategias de asignación del uso de la tierra en el espacio para conciliar la conservación de la diversidad biológica y la producción agrícola. Sin embargo, en este debate no se ha prestado suficiente atención a otros servicios ecosistémicos como los de aprovisionamiento o regulación, tal como el almacenamiento de carbono. Adicionalmente, no se ha investigado suficientemente enfoques híbridos que vayan más allá de la aparente dicotomía, *land sparing*-*land sharing*. En este capítulo se exploraron los posibles efectos de diferentes configuraciones de paisaje en el almacenamiento de carbono en el suelo y en la biomasa aérea. Se recolectaron datos secundarios a través de una revisión bibliográfica y se aplicó el modelo de almacenamiento y secuestro de carbono InVEST para estimar el almacenamiento de carbono en ocho escenarios anticipatorios a nivel municipal. Tres escenarios representaron un aumento del almacenamiento de carbono en relación con la línea base de 2015, a saber, el escenario de *regeneración natural* con un aumento de +14,3%, el escenario agroforestal *basado en palma y cacao* con un +2,4%, y el escenario de *mosaico híbrido con* un aumento de +10,6%. Los escenarios en los que la expansión agrícola dio lugar a la deforestación indicaron pérdidas sustanciales de carbono (-12,7 y -40,6%), mientras que los escenarios basados en sistemas agroforestales dieron lugar a pérdidas de carbono reducidas (-1,3 a -4,6%). Los resultados de este capítulo sugieren la importancia de la regeneración natural de los bosques secundarios como estrategia de gestión de la tierra para incrementar el almacenamiento de carbono en el paisaje. Además, estos resultados indican que la combinación de estrategias de tierras *land sparing* y *land sharing* a escala municipal puede ser un modelo útil para alimentar la elaboración de políticas orientadas a la multifuncionalidad del paisaje en Paragominas.

En conclusión, los resultados de esta investigación muestran que, dada la influencia de mercados globalizados, diversidad de percepciones, patrones de intensificación y *trade-offs* entre servicios ecosistémicos, alcanzar la multifuncionalidad del paisaje en Paragominas dependerá, en gran medida, de proyectos de ordenamiento territorial y gobernanza local que puedan revalorizar los bosques como parte integral del desarrollo socioeconómico. Dicha revalorización podría orientar las decisiones de productores rurales hacia estrategias de intensificación agrícola sostenible, más allá del actual modelo agroindustrial, sustentado en el paradigma *land sparing,* arraigado en la región. Por lo tanto, los resultados de esta tesis pueden proporcionar información a procesos políticos en curso en Paragominas, que pretenden dilucidar esquemas de gobernanza, donde el ordenamiento territorial, asume un papel central en el debate para desarrollar paisajes multifuncionales.

List of publications

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<u>*Peer reviewed journal articles*</u>

Pinillos, D., Bianchi, F.J.J.A., Poccard-Chapuis, R., Corbeels, M., Tittonell, P., and Schulte, R.P.O. (2020). Understanding Landscape Multifunctionality in a Post-forest Frontier: Supply and Demand of Ecosystem Services in Eastern Amazonia. Frontiers in Environmental Science 7(206). doi: 10.3389/fenvs.2019.00206.

<u>*Under review*</u>

Pinillos, D., Poccard-Chapuis, R., Bianchi, F.J.J.A., Corbeels, M., Timler, C., Tittonell, P., Ballester, M.V., and Schulte, R.P.O. Landholders' perceptions on Legal Reserves and agricultural intensification: diversity and implications for forest conservation in eastern Amazonia.

Pinillos, D., Corbeels, M., Poccard-Chapuis, R., Ballester, M.V., Tittonell, P., Schulte, R.P.O., and Bianchi, F.J.J.A. Exploring land sparing and land sharing strategies to implement tree-based systems and enhance carbon storage in eastern Brazilian Amazonia.

<u>*To be submitted*</u>

Pinillos, D., Bianchi, F.J.J.A., Poccard-Chapuis, R., Tittonell, P., Schulte, R.P.O., Corbeels, M. Characterizing farm diversity in the eastern Amazon region: implications for agricultural intensification in a transitioning frontier.

Poccard-Chapuis, R., Plassin, S., Osis, R., **Pinillos, D**., Pimentel Martinez, G., Thalês, M., Laurent, F., de Oliveira Gomes, M., Ferreira, L., Carvalho Peçanha, J., and Piketty, M.G. Mapping land suitability to drive landscape restoration in the Amazon.

Poccard-Chapuis, R., Thalês, M., Plassin, S., **Pinillos, D**., Osis, R., Laurent, F., de Oliveira Gomes, M., Ferreira, L., Carvalho Peçanha, J., and Piketty, M.G. Landscape restoration in the Brazilian Amazon: Retrospective analysis in a typical post-frontier jurisdiction.

Pinillos, D. and Azurdia, D. Landscapes of slow violence in Latin America: scales, narratives, and perspectives to rethink human-nature interactions.

Conference proceedings

Pinillos, D., Bianchi, F.J.J.A., Poccard-Chapuis, R., Corbeels, M., Tittonell, P., de Oliveira, M.R., Schulte, R. 2018. Mapping the supply and demand of ecosystem services: a first step towards multifunctional land management in eastern Amazonia. Poster prepared for the SDG-conference 'Towards Zero Hunger:

Partnerships for Impact', Wageningen. https://www.wur.nl/en/Research-Results/Sustainable-Development-Goals/SDG-Conference-Towards-Zero-Hunger/Poster-sessions.htm

Poccard-Chapuis, R., Plassin, S., Peçanha, J., Laurent, F., Piketty, M.G., Pimentel, G., Bourgoin, C., **Pinillos, D.**, Osis, R., Blanc, L., Gomes, M., Gond, V., Betbeder, J., Dessard, H., Pacheco, P. 2019. Landscape restoration in the Amazon: land suitability and jurisdictional governance to achieve ecologic and economics goals. GLP 4th Open Science Meeting 2019, 24-26 April 2019, Bern, Switzerland. Oral Presentation. https://agritrop.cirad.fr/594965/

Training and education

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (4.5 ECTS)

- Understanding landscape multifunctionality in a post-forest frontier: supply and demand of ecosystem services in Eastern Amazonia

Post-graduate courses (7.5 ECTS)

- International/specialist course: agricultural transformation and rural innovations field course in Kyotera, Uganda; University of Copenhagen (2016)
- Geostatistics; PE&RC, SENSE (2018)

Deficiency, refresh, brush-up courses (6 ECTS)

- System analysis, simulation and system management; PPS, FSE (2016)

Competence strengthening / skills courses (3.7 ECTS)

- Competence assessment; Wageningen Graduate Schools (2015)
- Brain training; Wageningen Graduate Schools (2016)
- Scientific writing; Wageningen Graduate Schools (2017)
- Effective behaviour in your professional surroundings; Wageningen Graduate Schools (2017)

Scientific integrity / ethics in science activity (0.3 ECTS)

- Ethics in plant and environmental sciences; Wageningen Graduate Schools (2019)

PE&RC Annual meetings, seminars and the PE&RC weekend (2.1 ECTS)

- PE&RC First years' weekend (2015)

- PE&RC Midterm weekend (2017)
- PE&RC Last years' weekend (2018)

National scientific meetings / local seminars / discussion groups (4.4 ECTS)

- Sustainable intensification of agricultural systems; the Netherlands (2016)
- Plant soil interactions; the Netherlands (2016)
- PhD Seminar at Embrapa Oriental; Brazil (2016)
- First international workshop Forefront; the Netherlands (2016)
- Yearly thesis committee at SupAgro; Montpelier, France (2016-2019)
- Farmers' values and landscapes designs; Paragominas, Eastern Amazonia, Brazil (2017)
- Group presentation; FSE, the Netherlands (2017)
- Update seminar on PhD project at Embrapa Oriental; Brazil (2017)
- Functional land management FSE workshop; the Netherlands (2018)
- Creating a global classroom in sustainable foodscapes: virtual and augmented reality application in education and its challenges; the Netherlands (2018)
- PhD Seminar; Luiz de Queiroz College of Agriculture University of São; Brazil (2020)

International symposia, workshops and conferences (3.2 ECTS)

- 21st World Congress of Soil Science; Rio de Janeiro, Brazil (2018)
- SDG Conference Towards Zero Hunger: partnership for Impact; Wageningen, the Netherlands (2018)

Lecturing / supervision of practicals / tutorials (2.7 ECTS)

- System analysis, simulation, and system management (2017-2019)

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About the author

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Daniel was born on December 16, 1985 in Mexico City in the beautiful barrio of Coyoacán.

In the provincial state of Puebla, surrounded by its colonial architecture and the majesty of the Popocatépetl and Iztaccíhuatl volcanoes, he devoted his Mexican childhood to kicking a football and sculpting dinosaurs in plasticine.

In 1996 he returned with his little sister and his parents to his motherland, Guatemala, to reunite with a past that he did not live. In this place, the nostalgia of leaving Mexico was only comprehended by Lake Atitlán and the collection of smaller, yet just as magnificent volcanoes echoing the sounds he was used to hearing.

In high school under a rigid Jesuit education, he met friends with whom to travel, sing, and laugh at the unlaughable. He went on, and as a forestry student he found himself heading through the jungle to El Mirador. On top of the Mayan colossus, a sea of green invited him towards the unknown.

Europe became that unknown as he started a masters in Finland and Germany. The snow-covered forest at Koli, and then the Black Forest gently whispered at him tales about the perils of existence, silviculture, and boundless human contradictions.

In 2015, he started a PhD in the Netherlands and France to investigate a distant landscape in the Brazilian Amazon. After five years of physical, intellectual, and emotional endeavor, his personal interpretation revolved around the exquisite experience of embracing vulnerability in order to prevail.

While the moon mirrors time and music rises as cathedrals, spiral waves will continue to be drawn.

◀ Chicacao, Guatemala

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